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High frequency components in bottlenose dolphin echolocation signals

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THESIS

HIGH FREQUENCY COMPONENTS IN BOTTLENOSE DOLPHIN ECHOLOCATION SIGNALS

by

Ronald W. Toland Jr.

September 1998

Thesis Advisor:	Thomas G. Muir
Co-Advisor:	Steven R. Baker

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Submitted in partial fulfillment
of the requirements for the degree of

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I. INTRODUCTION

The work described in this thesis is a continuing research effort started by the Applied Research Laboratories of the University of Texas at Austin (ARL-UT), and sponsored by the Office of Naval Research, into the analysis of biosonar signals. Researchers at ARL-UT have identified significant high-frequency components in dolphin echolocation signals [Ref.1]. The primary focus of the present research is to further examine these signals, and to conduct blind dolphin biosonar target detection experiments with and with-out high-frequency-absorbing screens. These experiments will assess the importance of these high frequencies in dolphin echolocation and identification.

A. BACKGROUND

Over the past 35 years, most acoustic experiments performed with dolphins have utilized hydrophones with a typical receiving sensitivity curve extending to only about 130 kHz. As a result, prior measurements on the dolphin echolocation signal typically show the main frequency components peaking at around 100 kHz. The prior work shows that the signal decays at frequencies approaching the hydrophone maximum receive sensitivity, typically around 130 to 150 kHz. [Ref. 2]

In a project summary report to the Office of Naval Research Biosonar Research Program entitled "Role of Nonlinear Acoustics in Biosonar," Professor Thomas Muir and his graduate student, Ms. Diane Blackwood of Texas A&M, summarized the results of experiments conducted in May 1997. These experiments were conducted at the Naval Command and Control and Ocean Surveillance Center (NRaD), in San Diego, California, and involved the bottlenose dolphin (*tursiops truncatus*) as well as the beluga whale (*delphinapterus leucas*). Their experiments proved that these species do emit higher frequency echolocation signal components, extending up to some four to five times what previous investigators have recorded.

Prior research on the bottlenose dolphin species has also reported the high resolution capability of marine biosonars to classify and distinguish between small man made targets. This reported level of resolution could not be achieved with man made sonars operating in the frequency range around 100 kHz. Cetacean biosonar performance reported in the literature has sometimes seemed to be in violation of a law in physics called the "Uncertainty Principle." This principle states that the best resolution an active sonar beam can achieve equals the sonar pulse duration times the medium sound speed, divided by two, ($c\tau/2$) [Ref. 3]. Using this relation, it is predicted that a dolphin projecting an individual click of 60 μs, at a hollow steel cylinder target, and using 1500 m/s for the sound speed of seawater, can achieve a best resolution of 4.5 cm. Previously reported biosonar experiments on dolphins have shown they are capable of achieving much higher resolution. The capability of a bottlenose dolphin to discriminate differences in the wall thickness of hollow steel cylinders was studied by Titov [Ref. 4]. The animal was able to react to a wall thickness difference of 0.2 mm at a 75% correct response level. The existence of high frequency signal components (greater than 100-150 kHz) may help to explain why a dolphin can achieve a much higher resolution than permitted by this law in physics. [Ref. 1]

The dolphin's ability to recognize and classify targets buried in the sediments, in reverberation limited environments, is better than any man-made mine-hunting sonar system. In fact, marine mammals, although cumbersome, and expensive, are currently the only means the Navy has for detecting buried mines [Ref. 5]. Therefore, a brief description of the current U.S. Navy Marine Mammal Program is given in section C.

B. RESEARCH MOTIVATION AND OBJECTIVES

This thesis describes the results of an investigation into the effect of the insertion of a filter which suppresses the high frequencies on the dolphin's ability to classify targets. This thesis research has significance to both the military and commercial interests. For the military, the understanding of biosonar mechanisms and signal production can be utilized in improving the resolution of U.S. Navy sonar systems, which

have a much higher area search rate than marine mammals. An understanding of the mechanisms that enable dolphins to detect buried mine-like objects could lead to considerable improvements in man-made sonar systems for buried mine detection and classification. This knowledge would also greatly improve the biological and physical modeling of animal acoustic systems.

C. U. S. NAVY MARINE MAMMAL PROGRAM

The Navy's Marine Mammal Program incorporates specially trained Atlantic and Pacific bottlenose dolphins, white whales, and sea lions for mine detection and neutralization, swimmer defense, and recovery of exercise mines and torpedoes. Taking advantage of years of evolution that have produced animals well suited for these tasks, the Navy has evolved complex and sophisticated training techniques that enable these animals to conduct real-world operations. [Ref. 5]

The Marine Mammal Program began in 1960, when several dolphins were used in hydrodynamic studies addressing underwater torpedo design. In 1963, the Navy began studying the animals' deep diving and echo-location capabilities, and determined that dolphins could work untethered in the open ocean. In the late 1960's the Navy developed a dolphin swimmer detection and marking system under the code name Short Time. It deployed to Cam Rahn Bay in 1970, to guard an ammunition pier that had been the target of attacks by the Vietcong. Once the dolphins were on scene, the raids stopped. In 1987, six Pacific bottlenose dolphins provided underwater surveillance and detection capability to support bases in the Persian Gulf. [Ref. 5]

The Navy's operational Marine Mammal System includes four to eight marine mammals which can be easily deployed on very short notice by strategic airlift to any part of the world and can be worked from ships in forward areas. The system is divided into four programs utilized by the fleet, three of which include bottlenose dolphins:

- Mk 4 Mod-0 – Pacific bottlenose dolphins detect mines and attach neutralization charges on the mooring cables of tethered mines moored near

the bottom. The Navy is expanding this system's capability to neutralize all tethered buoyant mines.

- Mk 6 Mod-1 – Dolphins provide defense of harbors, anchorages, and individual ships against swimmers and divers. The Mk 6 participates regularly in fleet exercises and real-world base security, providing a comprehensive surface and subsurface swimmer detection.
- Mk 7 Mod-1 – Dolphins detect, locate, and mark or neutralize bottom mines and buried mines. This animal system represents the only operational buried-mine detection and neutralization capability in the world today.

The Mk4 and Mk7 Marine Mammal System detachments are integral operational elements of the Navy's mine countermeasures forces and have demonstrated the capability to operate for extended periods from ships forward deployed. [Ref. 6]

There is also an additional system under development; Experimental 8 Marine Mammal System will employ six dolphins for exploration and reconnaissance of in-volume moored and bottom mine-like contacts in the Very Shallow Water Zone (10-40 foot depth). The Ex 8 dolphins will be deployable from an Amphibious Task Force ship for low-visibility, minefield exploration and reconnaissance [Ref. 7].

The dolphins in the Marine Mammal Program satisfy critical requirements and real world operational needs that today cannot be met as effectively or efficiently in any other way.

D. THESIS OUTLINE

The second chapter provides a description of the dolphin echolocation system and characteristics of biosonar signals recorded with a wide band hydrophone. The third chapter describes the theory and laboratory experiments conducted on absorptive acoustic screens. The fourth chapter explains the procedure and initial results using an acoustic filter to suppress high frequencies and its effects on the dolphin's ability to classify targets. The final chapter provides concluding remarks and recommendations for continuing research efforts.

II. DOLPHIN ECHOLOCATION SYSTEM

This chapter will present a brief introduction to the dolphin biosonar transmission system and the characteristics of its biosonar signals. In addition, samples of bottlenose dolphin click trains will be analyzed to show that previously ignored and undetected high frequency echolocation signal components are indeed present.

A. DESCRIPTION OF THE DOLPHIN ECHOLOCATION SYSTEM

The term echolocation refers to an ability the dolphin possesses that enables it to "see" by listening for echoes. Figure 2.1 illustrates the echolocation process. The dolphin echolocation system is a highly specialized sonar that enables dolphins to explore their environment and search out their prey in a watery world where sight is often limited by dark, murky water cluttered with debris. How a dolphin produces and receives sound is still a highly controversial subject. Professor Ridgway proposed a predominant theory that the nasal plugs, under muscular control, produce sound in the form of acoustic transients as air passes between the plugs and the nasal walls [Ref. 8]. The frequency range of these "sonar clicks" is higher than that of the sounds used for communication, and differs between species. One current hypothesis is that this sound is projected into the water in a narrow beam after passing through a fatty melon which may act as a device to couple sounds produced deep in the skull into the water [Ref. 9].

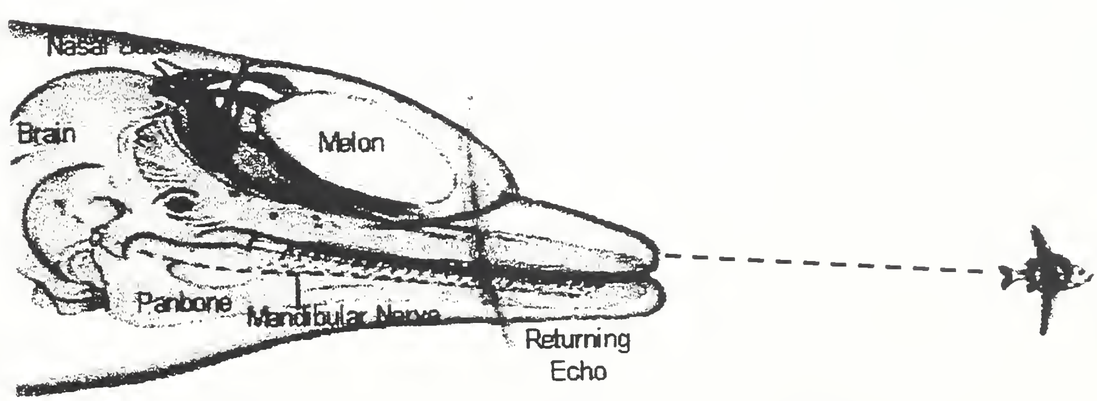


Figure 2.1 Dolphin Echolocation Mechanism After Ref. [10].

When the sound strikes an object, some of the energy of the sound wave is scattered back towards the dolphin. It has been postulated that sound waves in the water pass into the head of the animal and are transmitted to the ear region by a thin bony area in the panbone within the dolphin's lower jaw [Ref. 9].

The time lapse between click and echo could enable the dolphin to evaluate the distance between it and the object, as is the case in torpedo sonar, for example. Professor Au has speculated that the strength of the signal as it is received on the two sides of the dolphin's head may enable it to evaluate direction or localize sound [Ref. 2]. By continuously emitting clicks and receiving echoes in this way, the dolphin can track and find objects.

The echolocation system of the dolphin is extremely complex. Using only its acoustic senses, a dolphin can discriminate between practically identical objects, which differ by ten per cent or less in volume or surface area. It can do this in a noisy environment, can whistle and echolocate at the same time, and can echolocate on near and distant targets simultaneously.

B. DOLPHIN SONAR RESEARCH PRIOR TO 1997

Dolphins are capable of producing extremely short duration, broad bandwidth, acoustic signals, which are utilized for echolocation. The ability of dolphins to accurately perceive their environment and to perform difficult recognition and discrimination tasks depends on the characteristics of these biosonar signals and how they are emitted, and processed upon reception. Signal characteristics and projection patterns have been recorded and studied over a long period of time by many investigators, but the operational mechanisms of dolphin sonar yet remains unanswered.

A typical biosonar signal waveform and frequency spectrum of a bottlenose dolphin recorded in a tank environment by Evans in 1973 is shown in Figure 2.2 [Ref. 11]. The peak frequency (frequency of maximum energy) in this example was 52 kHz. Early bottlenose dolphin signals were measured in tanks, and it was generally believed that peak frequencies occurred in the vicinity of 30 to 60 kHz.

In 1974, Au observed significant energy, up to the limit of his detection system, within a dolphin click. This energy extended to much higher frequencies than were previously measured. He conducted target detection experiments in Kaneohe Bay, Oahu, Hawaii, which involved measuring two bottlenose dolphin echolocation signals in open waters. His results showed that the signals had peak frequencies between 120 and 130 kHz, which were over an octave higher than the peak frequencies recorded by Evans. The average waveform and frequency spectrum of a biosonar click train observed by Au is shown in Figure 2.3. [Ref. 2]

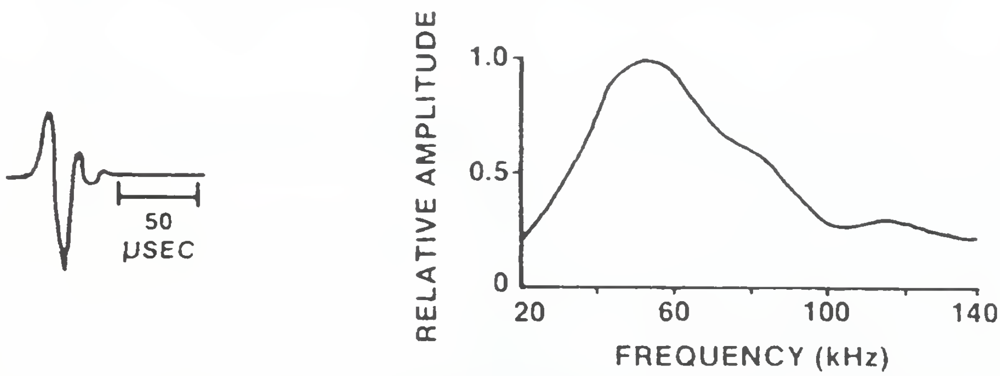


Figure 2.2 Typical Waveform And Frequency Spectrum of Bottlenose Dolphin in a Tank From Ref. [11].

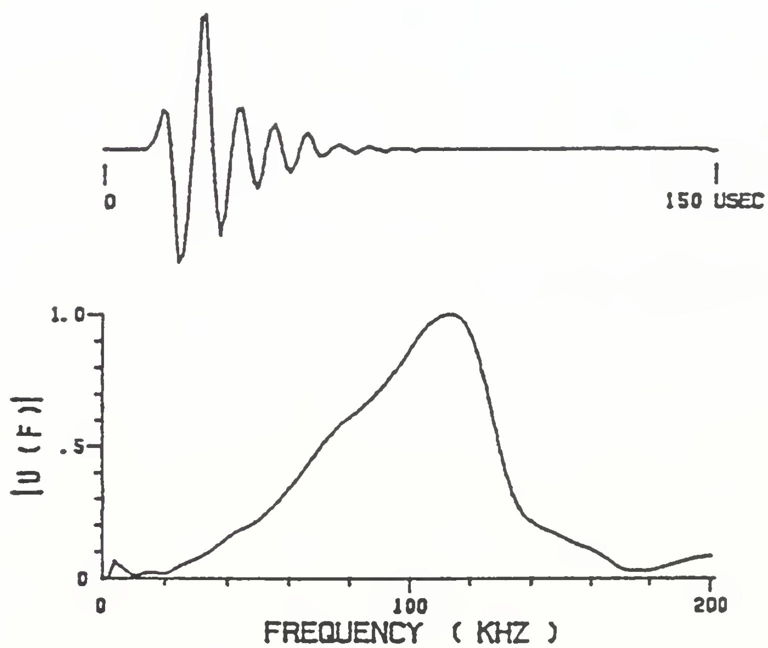


Figure 2.3 Average Waveform and Frequency Spectrum of Bottlenose Dolphin in Open Waters From Ref. [2].

Mitson published evidence of high-frequency acoustic emissions from a school of white beaked dolphin (*lagenorhynchus albirostris*) in the North Sea in 1987. While onboard a British fisheries research vessel, they just happened to record some fortuitous dolphin signals. These signals were detected by a sector side-scanning sonar of high bearing and time resolution, used as a passive listening device. The acoustic emissions from the dolphins had significant energy at frequencies around 305 kHz. Again, this was about one octave higher than previously observed. [Ref. 12]

C. RECENT BROADBAND MEASUREMENTS BY ARL-UT

The hydrophone frequency response of the prior measurements of Evans, Au, and Mitson never extended high enough to conclusively capture all of the high frequency components. The high resolution capability of cetacean sonars prompted ARL-UT to conduct further research into the existence of higher frequencies that may have been overlooked in prior research. The "Uncertainty Principle" hypothesis was proposed to the Office of Naval Research, who then funded its testing by the scientific method. The two species of dolphins recorded in 1997 by Muir, Blackwood, and Wilson in San Diego Bay were found to emit significant high frequency signal components extending to as high as 400 to 500 kHz [Ref. 1]. These signals were recorded using a hydrophone capable of measuring biosonar signals up to 2 MHz. Details of the hydrophone, experimental configuration, procedures, and results, are described below.

1. Wide Band Hydrophone Characteristics

The wide band hydrophone, designed by Mr. Lew Thompson at the Applied Research Laboratories, University of Texas at Austin, was made from a one centimeter diameter thin disk of piezo-composite material. This disk consisted of a mixture of piezo-ceramic and a plastic material that is inherently wide band. The transducer housing was made of a soft, thin polyurethane material. A castor oil bath coupling medium was used within the housing. Figure 2.4 shows a diagram of the hydrophone and the frequency response curve. Notice that the hydrophone is useful up to 2 MHz.

There is a notch present at 550 kHz, which will be eliminated in future designs. Below 500 kHz, the response curve is fairly flat and deviations from this flatness were corrected for in the data analysis. [Ref. 1]

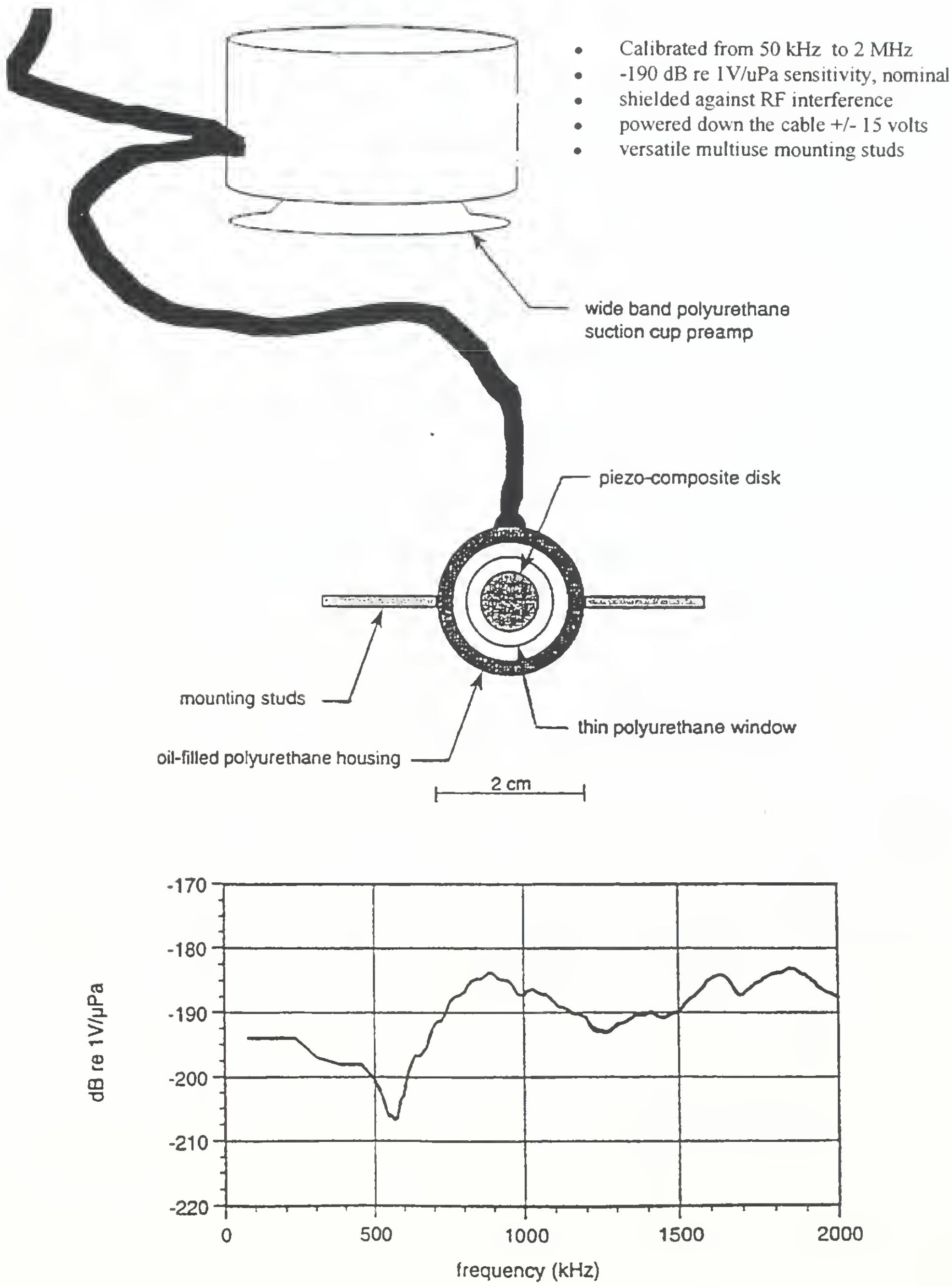


Figure 2.4 Wide Band Hydrophone and Receive Sensitivity Curve From Ref.[1]

2. Experimental Configuration

Recordings were conducted of the sounds emitted by two species of captive research dolphins in May and October 1997, at the Space and Naval Warfare Systems Center (SPAWARSYSCEN), in San Diego. The measurements utilized a bite bar, and targets consisting of hollow metal spheres, and bags of both rock and junk metal, as seen generically in Figure 2.5. First the dolphins were trained blindfolded and rewarded fish to eat for correctly identifying the different targets when they were lowered in the water. The animals indicated a positive classification by emitting a whistle, which can be heard by the trainers and scientists. Many data sets were acquired on two bottlenosed dolphins named Bertha and Slooper, as well as a beluga whale named Muk Tuk. A random sequence of designated real and false targets were serially offered to each animal during the course of the experiment, in order to keep the animals alert, functioning to their best capability, and to keep them "honest". [Ref. 1]

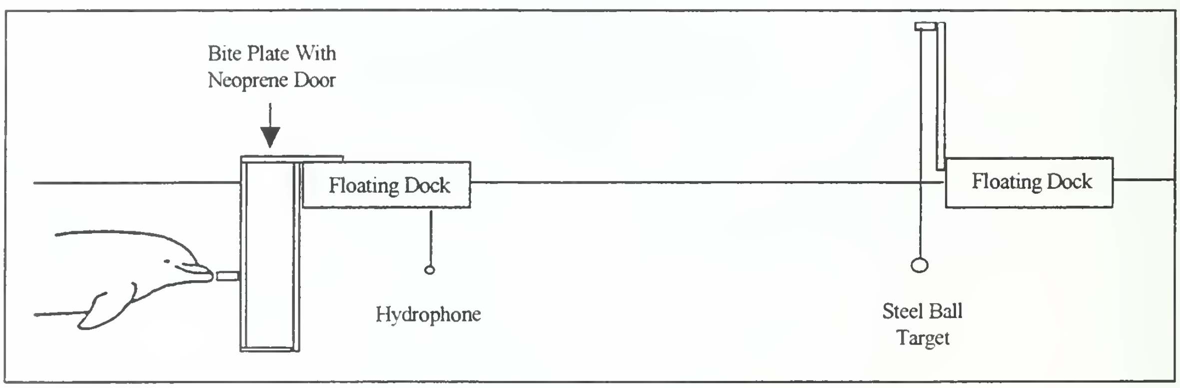


Figure 2.5 Generic Experimental Geometry

3. Experimental Results

Experiments on the dolphin were conducted with the bite bar at a depth of 0.71m, with the hydrophone on axis with the rostrum, and located at a range of 4.65m from the rostrum. The targets were placed at a distance of 9.0m from the bite bar. When the target is presented to the dolphin, it usually begins pinging on the target with a series of

rapid fire "clicks", often called a "click train." A raw data recording of a click train is shown in Figure 2.6. Notice that the click train consists of an increasing amplitude, followed by several pulses emitted at maximum amplitude, and finally a decaying amplitude. This figure also shows a gradually increasing time between clicks. In this example, there are 43 clicks in a time span of 1.2 seconds. The dolphin clicks are separated by about 23 msec, which, at the speed of sound in water, is the two way travel time to a target located at a range of about 21 meters. For these measurements, the range to the target was 9 meters, indicating that the echo from one click was received prior to the emission of the subsequent click [Ref. 1].

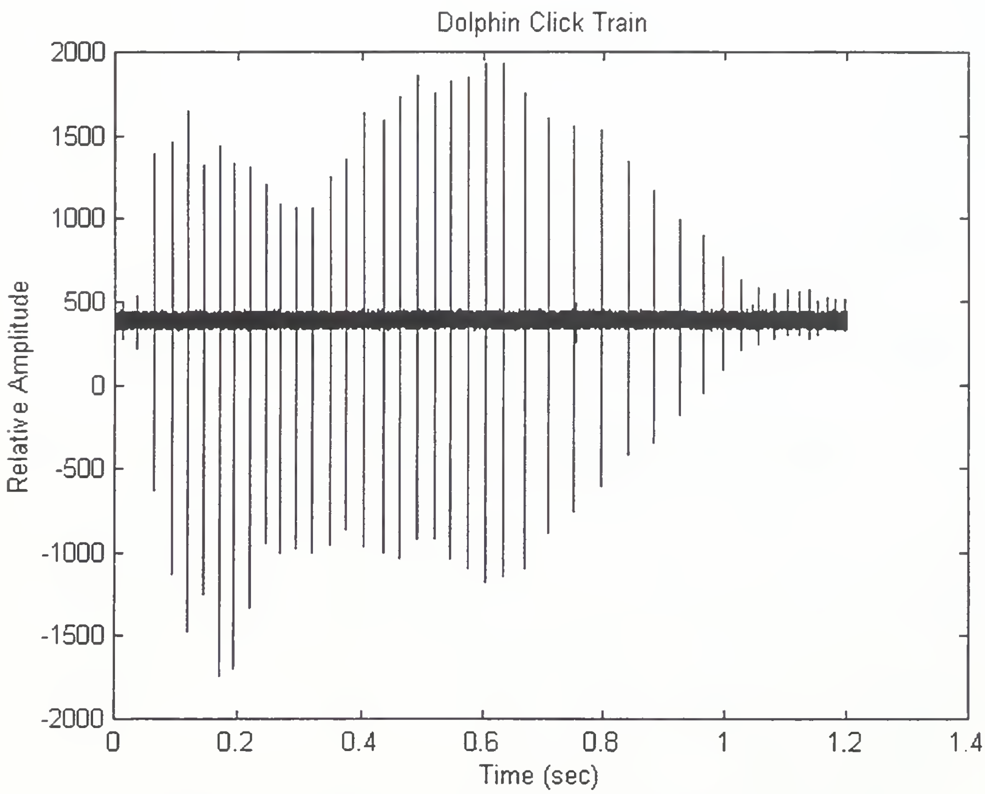


Figure 2.6 Bottlenose Dolphin Echolocation Click Train

Figure 2.7 shows one dolphin click from the middle of the "click train" in Figure 2.6. This raw data time series contains 128 digitization points and shows the relative amplitude of the signal versus time. As can be seen, the signal contains a few cycles of powerful transmission, followed by a few weak cycles of acoustic radiation. Kamminga suggests that these weak cycles may indicate where reverberations, possibly due to reflections inside the dolphin's head, against the skull or air sacs, interfere with the actual

first-emitted sonar signal [Ref. 13]. This time domain of the dolphin click also shows very sharp maximum and minimum peaks, which may contain very high frequency components.

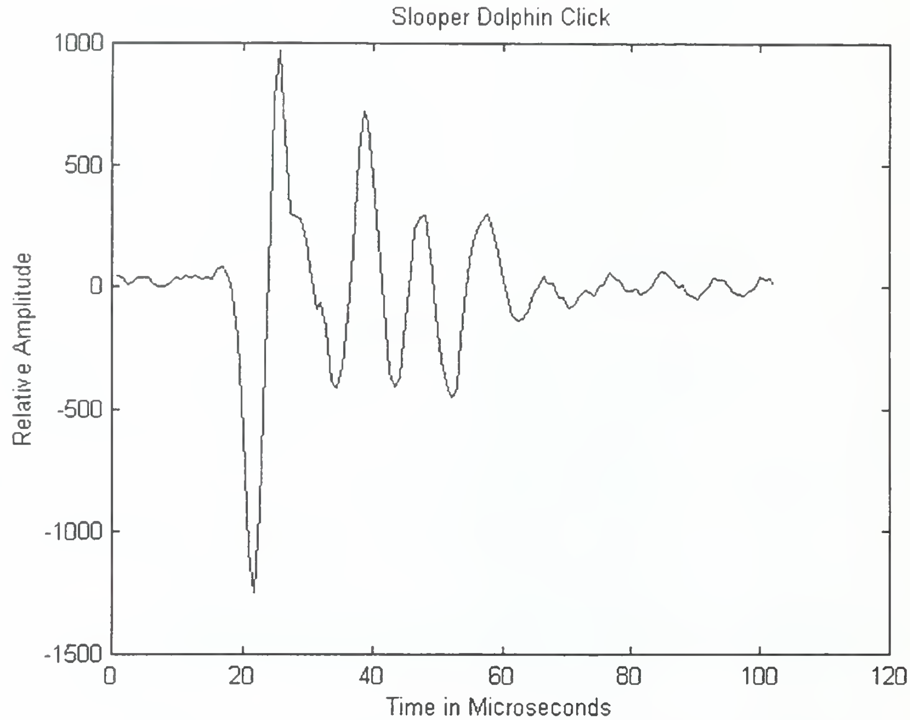


Figure 2.7 Bottlenose Dolphin Echolocation Click

A proper acoustic convention is to show the energy flux spectral density in a signal with units of pico-joules per meter squared-hertz [Ref. 14]. The energy flux spectral density of this bottlenose dolphin click was calculated using the MATLAB Program in Appendix A, and is presented in Figure 2.8. The program accounted for the frequency dependence of the ARL-430 hydrophone receive sensitivity. This figure compares the click plus noise to just noise (noise obtained just prior to the click train), and clearly shows significant energy present in the dolphin sonar signal at frequencies well above 200 kHz, much higher than previously reported. Utilizing the same MATLAB program, the energy flux spectral density was plotted for three separate clicks from the "click train" in Figure 2.6. These clicks were extracted from the beginning, middle, and end of the "click train." Figure 2.9 shows that the high frequency energy flux increases near the peak amplitude of the click train emissions.

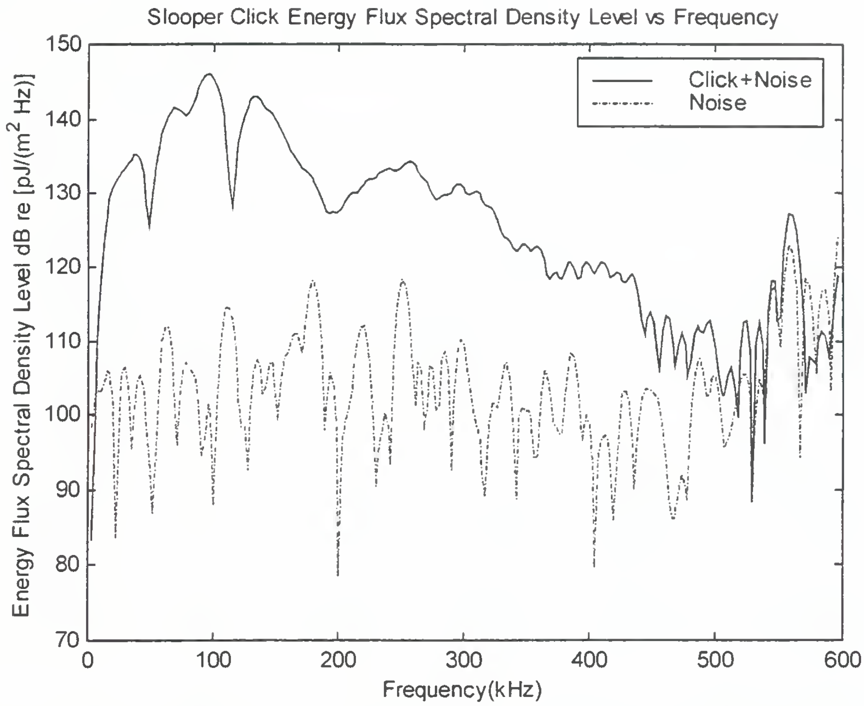


Figure 2.8 Energy Flux Spectral Density In A Dolphin Click

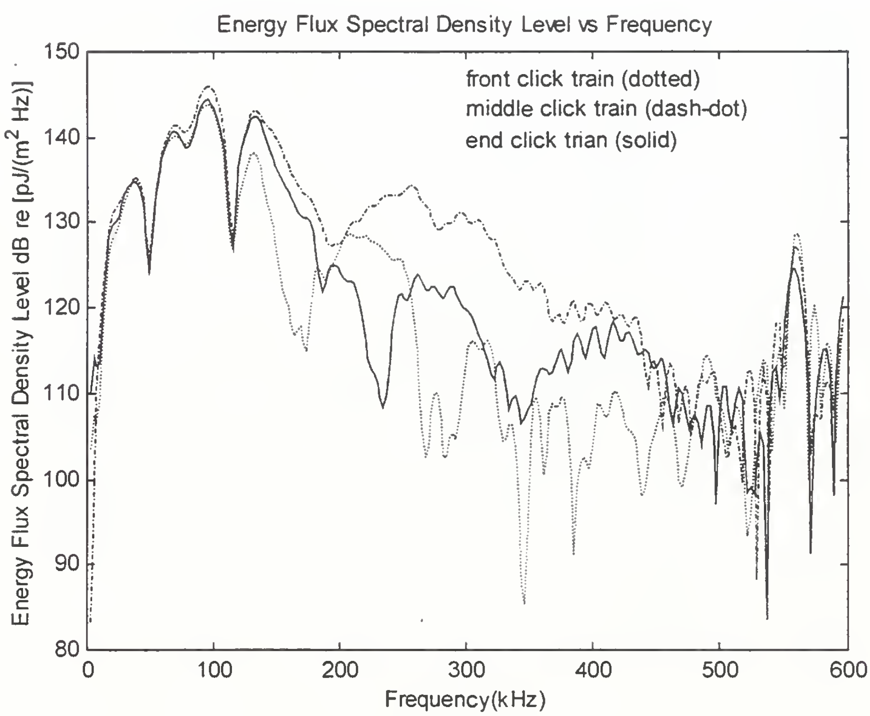


Figure 2.9 Shift of Energy Flux Spectral Density Through Click Train

Further analysis conducted on the dolphin "click train" in Figure 2.6 shows a great degree of repeatability among a sequence of clicks. Taking five consecutive signals from the middle of the "click train" and performing a cross-correlation, using the MATLAB program in Appendix B, produced maximum correlation coefficients ranging from 96-99%. The maximum correlation coefficients of the five signals can be seen in Table 2.1. Figure 2.10 shows a plot of the five signals aligned to a position where the signals best correlate to each other. There is little difference in the time series between the five clicks.

Signal	1	2	3	4	5
1	1.000	.9716	.9820	.9719	.9727
2	.9716	1.000	.9645	.9626	.9623
3	.9820	.9645	1.000	.9949	.9952
4	.9719	.9626	.9949	1.000	.9964
5	.9727	.9623	.9952	.9964	1.000

Table 2.1 Maximum Correlation Coefficients of Five Consecutive Dolphin Clicks

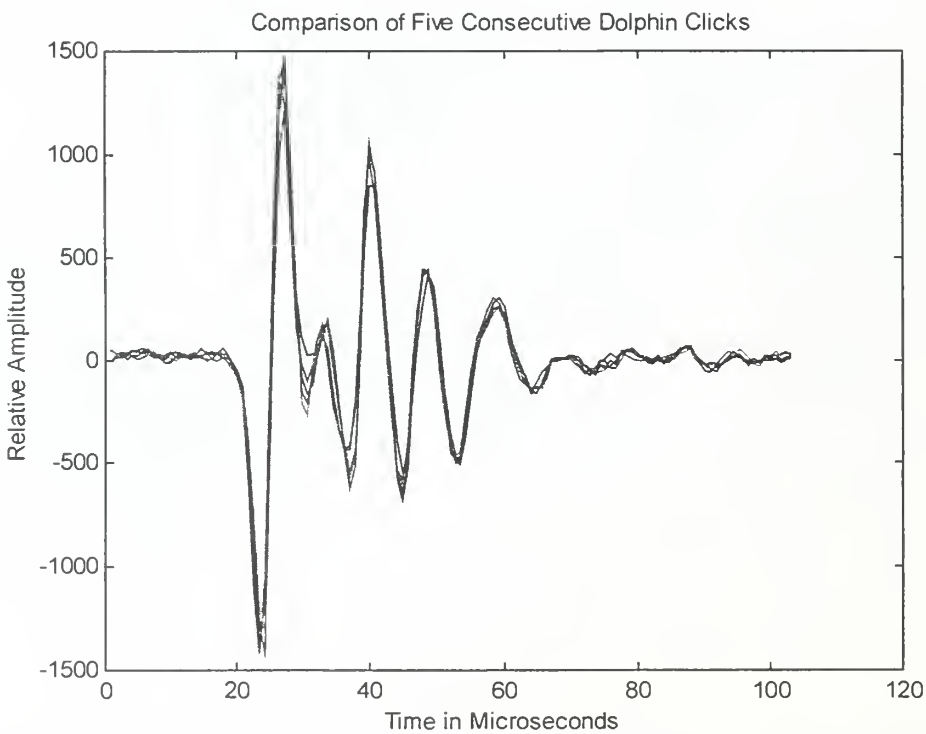


Figure 2.10 Comparison of Five Consecutive Clicks From A Click Train

This plot suggests that, if the high frequencies above 200 kHz are present in one click, then the high frequencies must also be present in other clicks from the maximum amplitude portion of the click train.

This chapter has briefly explained the dolphin echolocation system and described some past research conducted on high frequency echolocation components. It has also shown that much higher frequencies components are in fact present within a dolphin click. The next chapter will explain the selection of an absorbing screen that is being used to answer the question: is the dolphin using these high frequencies during echolocation?

III. SELECTION OF ABSORPTIVE ACOUSTIC SCREENS

The question remains as to whether or not the dolphin is actually using the newly discovered high frequency components described in Chapter Two. In order to test this hypothesis, Dr. Muir proposed to ONR that an experiment be performed in which an acoustic filter to suppress the high frequencies is placed between a dolphin and a target, and it is determined whether the dolphin's ability to detect a target is impaired. This chapter will describe the theory, selection, and laboratory experiments conducted on various materials for this purpose.

A. INSERTION LOSS AND REFLECTION LOSS THEORY

Anechoic coatings, and bulk absorbing materials ideally reflect zero percent of sound incident upon them, and therefore present themselves as a good absorber. These materials can be evaluated by measuring the percentage of sound transmitted through and reflected from the material when a sample is immersed in water. These two measured characteristics, called the "insertion loss" and "reflection loss," are defined by Equations 3.1, and 3.2 respectively.

$$\text{Insertion loss} = 20\log\left(\frac{\text{Incident rms sound pressure}}{\text{Transmitted rms sound pressure}}\right) \tag{3.1}$$

$$\text{Reflection loss} = 20\log\left(\frac{\text{Incident rms sound pressure}}{\text{Reflected rms sound pressure}}\right) \tag{3.2}$$

Plane-wave propagation is assumed in both definitions, and both characteristics are expressed in positive decibel units. [Ref. 15]

Insertion loss is the reduction in the signal, in decibels, caused by inserting the material between the sound source and the receiver, with diffraction and refraction effects absent. The insertion loss of the material is due to the combination of sound reflected from the material and sound absorbed in the material, as illustrated in Figure 3.1. It is also a function of the material's dimensions and properties. When plane waves impinge

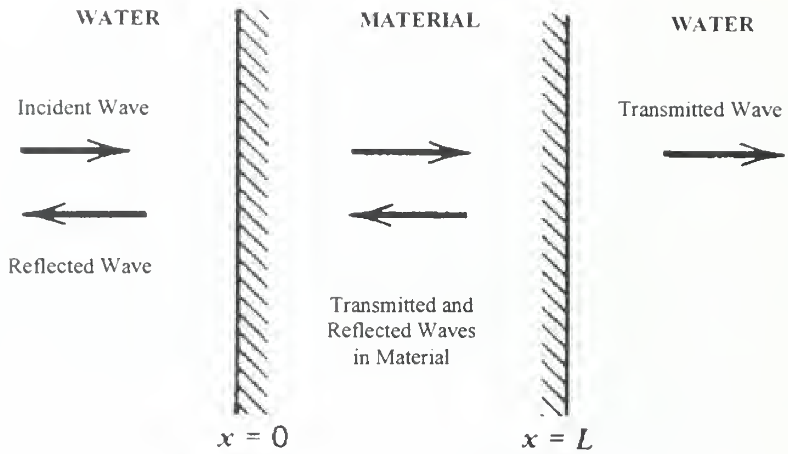


Figure 3.1 Reflection and Transmission of Plane Waves Normally Incident on a Layer After Ref. [3].

normally on a plate of a homogeneous absorbing material of uniform thickness, and water is on both sides of the plate, the theoretical insertion loss is given by:

$$IL = 20\log\left|\frac{(m+1-jr)^2\exp(j2kd)-(m-1+jr)^2\exp(-2\alpha d)}{4m(1-jr)\exp(jkd-\alpha d)}\right| \tag{3.3}$$

where m is the real ratio of the characteristic impedance of the material to the characteristic impedance of water ($\rho c/\rho_o c_o$), k is the wave number (ω/c), d is the thickness of the sample material in meters, α is the longitudinal attenuation constant in Nepers/meter, and r is the loss parameter of the material, defined by Equation 3.4.

$$r = \frac{\alpha}{\omega c} \tag{3.4}$$

In applying Equation 3.3 in this present investigation to model the behavior of the sound absorbing materials, α was taken to be at most a quadratic function of the frequency f:

$$\alpha(f) = af + bf^2 \tag{3.5}$$

The coefficients a and b can be determined by curve fitting Equation 3.3 to the experimental data for the acoustic absorbing panel, or they can be measured directly in a large material sample. [Ref. 16]

Reflection loss is a measure of how much the incident sound pressure level is reduced upon reflection, and depends on the acoustical impedance mismatch at the reflection boundary. The boundary acoustical impedance in turn depends on the material itself, and its thickness. Anechoic coatings often consist of a layer of rubber material mixed with either low-acoustic-impedance air voids or high-acoustic-impedance metal particles or both. The coating should have a good impedance match with the water so the sound energy will not be reflected, and after entering the coating, the sound energy should optimally be absorbed, otherwise the sound will be reflected at some subsequent boundary. [Ref. 15]

Theoretical reflection loss can be computed for sound incident normally on a uniform plate or panel of absorbent material immersed in water, and is given by:

$$RL = 20\log\left|\frac{[(m+1-jr)/(m-1+jr)]\exp(jkd+\alpha d)-[(m-1+jr)/(m+1-jr)]\exp(-jkd-\alpha d)}{\exp(jkd+\alpha d)-\exp(-jkd-\alpha d)}\right| \quad (3.6)$$

where m, kd, α, and r are the same as in Equation 3.3. In applying Equation 3.6 to model the behavior of the sound absorbing material, α was again taken to be a quadratic function of frequency. Reflection loss is a maximum for frequencies at which the panel thickness is a multiple of a half wavelength. [Ref. 16]

B. LIQUID MOLDING COMPOUND INVESTIGATION

Attempting to find a material with the correct properties to act as a low pass filter proved quite challenging. Experimentation first involved the testing of over the counter liquid molding compounds. The liquid molding was blended in a household blender to introduce air bubbles. The molding compound was then poured into a wooden mold and allowed to set for 12 hours. As the material solidified, the air bubbles migrated toward the top of the material. The final result was a substance composed of small air bubbles at the bottom of the sample and larger bubbles near the top. This material was expected to

act as a lossy acoustic medium allowing sound to transmit through the small bubble side with attenuation, and reflecting off the large bubble side. Measuring the insertion loss on numerous tiles with different thickness and bubble consistency showed the material to be nonabsorptive and purely reflective over the frequency range of 60 to 400 kHz. Insertion loss experiments were also conducted on open cell foam as recommend by Undersea Warfare Center, Newport RI. Again these materials were purely reflective and non-absorbing over the same frequency range. The search for an ideal absorbing tile ended when two pieces of SOAB, *sound absorbing material*, were discovered in one of the acoustic laboratories at the Naval Postgraduate School.

C. SOAB PROPERTIES AND TESTING

Sound absorbing material (SOAB) was first invented by the Germans in World War II. The German "Alberich" coating, consisting of a rubber layer with air-filled voids, was experimentally cemented to the outside of a number of U-boats [Ref. 17]. SOAB is a porous panel made from butyl rubber imbedded with aluminum powder. Microscopic air bubbles become attached to the aluminum powder surface in the manufacturing process. The sound absorption is dependent upon these air bubbles. In the 1950's, B. F. Goodrich Company of Akron, Ohio, made commercially available three different types of sound absorbing panels: SOAB I, SOAB II, and SOAB III. Each of these coatings consisted of different aluminum powder loads which varied the material's density. The absorbing material was researched as anechoic coatings for acoustic test tank lining to absorb reflections. In 1961, B. F. Goodrich produced a plot showing the transmission loss versus frequency for a SOAB baffle as a function of thickness. The plot, shown in Figure 3.2, did not mention the type of SOAB, and the frequency range only extended up to 60 kHz. [Ref. 18]

The first important parameter measured in order to determine the effectiveness of SOAB for use as an acoustic filter was the insertion loss. Tests were performed in a small anechoic tank designed for ultrasonic research. The four sides and bottom of the

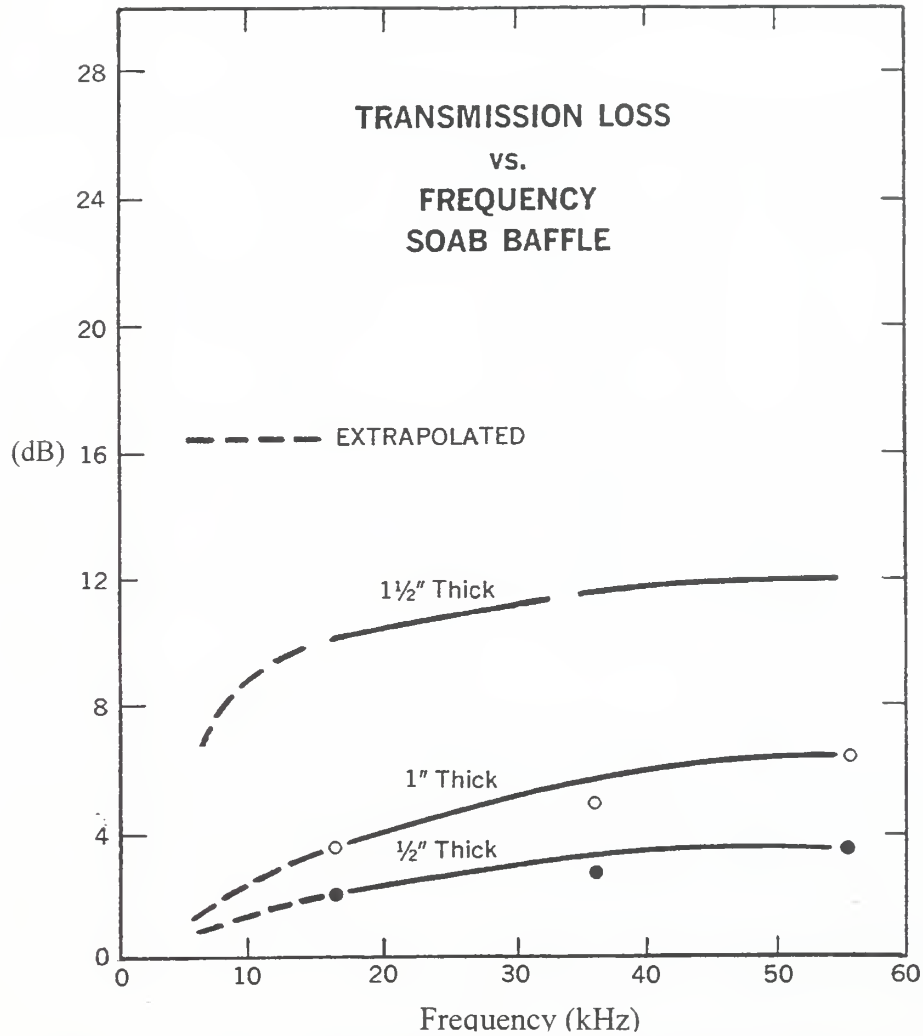


Figure 3.2 SOAB Transmission Loss versus Frequency From Ref. [18].

tank are shaped like "butterfly wings" to reduce the effect of standing waves and reflections, as described by Willette and Muir [Ref. 19]. The experiment consisted of a transducer projecting a tone burst of sound toward a hydrophone, and measuring the received hydrophone output voltage. The experiment geometry can be seen in Figure 3.3. The hydrophone was placed 30 cm from the transducer to ensure meeting far field criteria. The absorbing filter was placed between the projector and the receiver and the voltage was again recorded. The insertion loss was calculated by substituting the measured voltages for the pressure terms and rewriting Equation 3.1 as:

$$IL = 20\log\left|\frac{V_i}{V_t}\right| \tag{3.7}$$

where IL is the insertion loss in decibels, V_i is the direct hydrophone receive voltage, and V_t is the hydrophone receive voltage through the material.

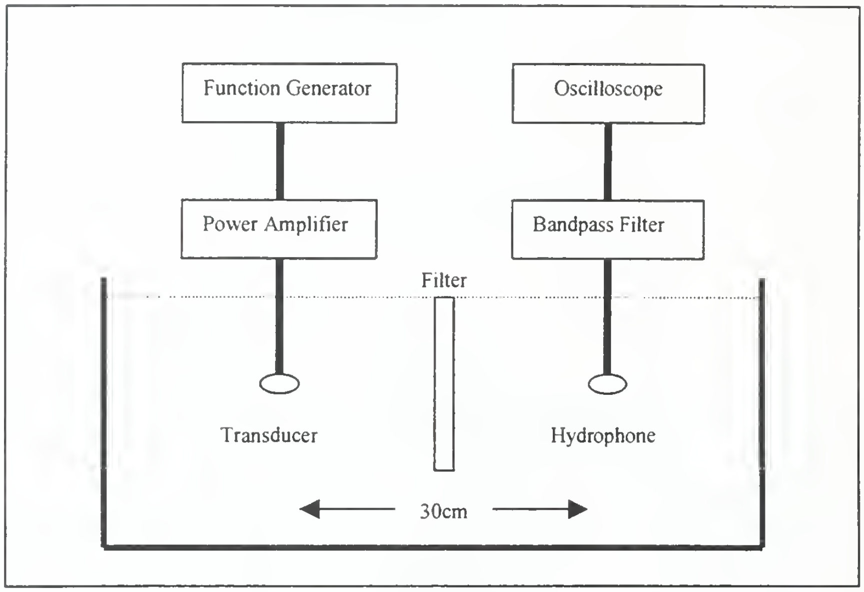


Figure 3.3 Geometry For Insertion Loss Experiment

The second parameter measured for the acoustic filter was reflection loss. Minimizing reflections off the absorbing filter is desirable, so as not to confuse the dolphin with reflected signals other than from the target. These measurements were performed in the same anechoic tank as described above. The experiment consisted of a transducer projecting pulsed sound, a hydrophone, and a sample tile as shown in Figure 3.4. The hydrophone was placed 50cm from the projector, without the filter present, and the receive voltage was recorded. The filter was then placed in the tank at 50 cm from the projector and the hydrophone moved to 25cm , halfway between the projector and the filter. The hydrophone receive voltage was again recorded. Correcting for spherical spreading, the reflection loss was calculated using:

$$RL = 20\log\left|\frac{V_i}{V_r}\right| \tag{3.8}$$

where RL is the echo reduction in decibels, and V_i and V_r are the hydrophone receive voltages with and without the filter respectively.

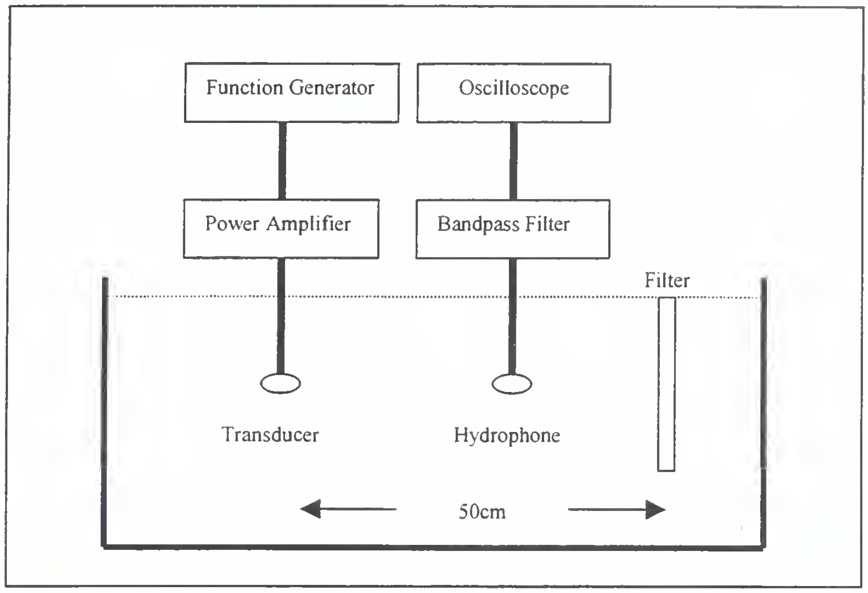


Figure 3.4 Geometry For Reflection Loss Experiment

D. EXPERIMENTAL RESULTS

The results from the insertion loss experiment are shown in Figure 3.5. Insertion Loss was measured on SOAB I ¼"-thick sample, SOAB III ½"-thick sample, and for both SOAB I and SOAB III together, making a ¾"-thick sample. Figure 3.5 shows that increasing the thickness of the SOAB screen also increases the insertion loss. As stated in the beginning of this chapter, it is desired to use these absorbing filters to suppress the high frequencies above 100-150 kHz and determine the dolphin's ability to detect targets with and without the filters. Of the choices available, the optimal filter to use in this application would be the SOAB III ½"-thick, because it has the least amount of absorption at the lower frequencies, and yet provides a greater absorption at the higher frequencies to suppress them. It should be mentioned that the total insertion loss is twice that shown in Figure 3.5 due to the two way travel through the absorbing screen.

Since the absorbing screens would be hanging underwater during the actual experiment with the dolphin, it was of interest to measure the insertion loss as a function of incidence angle. Even though the screen would be tethered so as to restrict its movement, there might be slight movement during the open ocean experiment. Figure 3.6 shows the Insertion Loss of the ½"-thick screen as a function of incidence angle off

axis. As one can see, there is only a slight variation in insertion loss with incidence angle for nearly normal incidence.

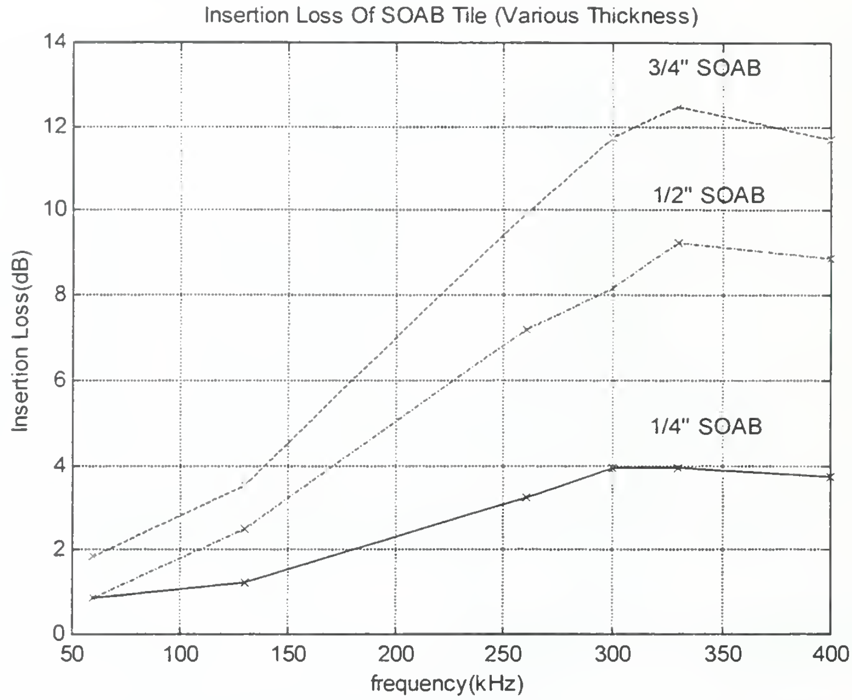


Figure 3.5 Insertion Loss vs Frequency For Three SOAB Samples

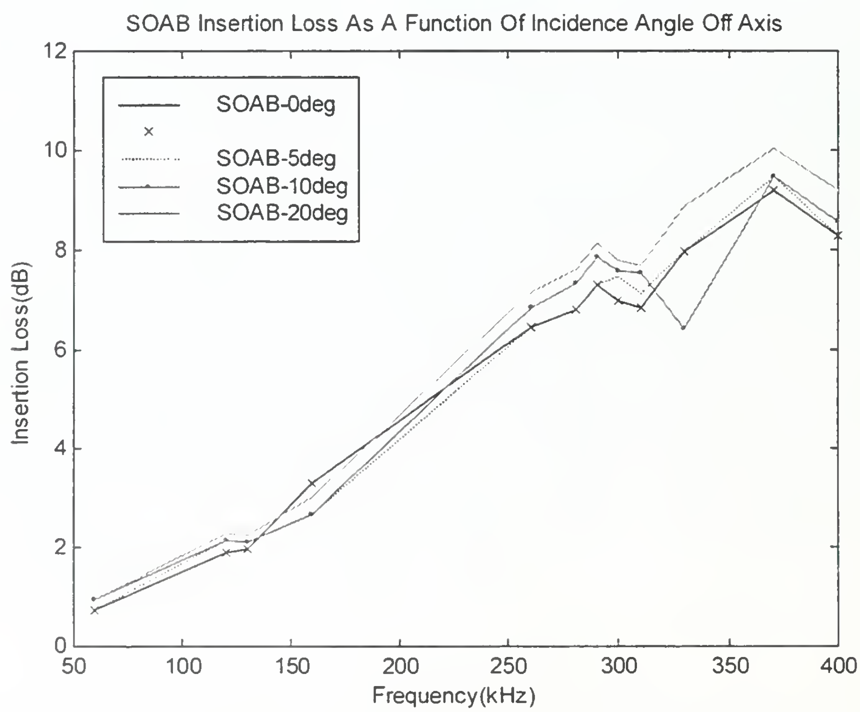


Figure 3.6 Insertion Loss vs. Incidence Angle Off Axis For ½" SOAB

In comparing theory (Equations. 3.3 and 3.6) to recorded measurements, it was necessary to obtain an accurate value for the ratio of acoustic impendances m, and to measure the impedance for both pieces of absorbing filters. First, the density of each material was calculated by weighing a small sample of the material and then submersing the piece in water, and measuring the volume of water displaced. The weight divided by volume of SOAB I (¼") and SOAB III (½") resulted in densities of 1520 kg/m^3, and 993 kg/m^3, respectively.

The speed of sound in each material was estimated from measurements of the time change or phase shift of the received signal zero axis crossings with and without the filter present. The filter was placed directly in front of the hydrophone, with its shortest axis being parallel to the direction of propagation. The time change of the zero axis crossings was measured near the beginning and middle of the received tone burst at 60 kHz, and 130 kHz, with an accuracy of plus or minus 0.01 microseconds. The filter sound velocity could then be calculated by:

$$C_s = \frac{C_w d_s}{d_s - C_w \Delta t} \tag{3.9}$$

where C_s and C_w are the sound speed in the filter and water respectively, d_s is the filters thickness, and Δt is the time shift. Using Equation 3.9 and the averaged time shift produced a velocity of 1586 m/s for SOAB I, and 1662 m/s for SOAB III.

The measured insertion loss for the ½" SOAB filter is plotted against theory in Figure 3.7. The theory curve was calculated using Equation 3.3, and making a number of successive approximations for the coefficients a and b in Equation 3.5, until the theory best matched the experimental data visually. Theory and experimental matched best when values of a and b where chosen as 0.20 Np/m/kHz^2, and 12 x 10^{-5} Np/m/kHz^2, respectively.

It was also necessary to measure reflection loss in our ½" SOAB filter, to minimize the reflected dolphin echolocation signal from the front surface of the filter. Reflection Loss was measured and compared with theory in Figure 3.8. The theory curve was calculated using Equation 3.6, and again choosing the same values for a and b in equation 3.5, until theory best matched experimental data visually. This figure clearly

shows that reflection loss theory is a maximum for frequencies at which the absorptive screen thickness is a multiple of a half wavelength. The reflection loss shows that the screen is non-reflecting, even at the higher frequencies.

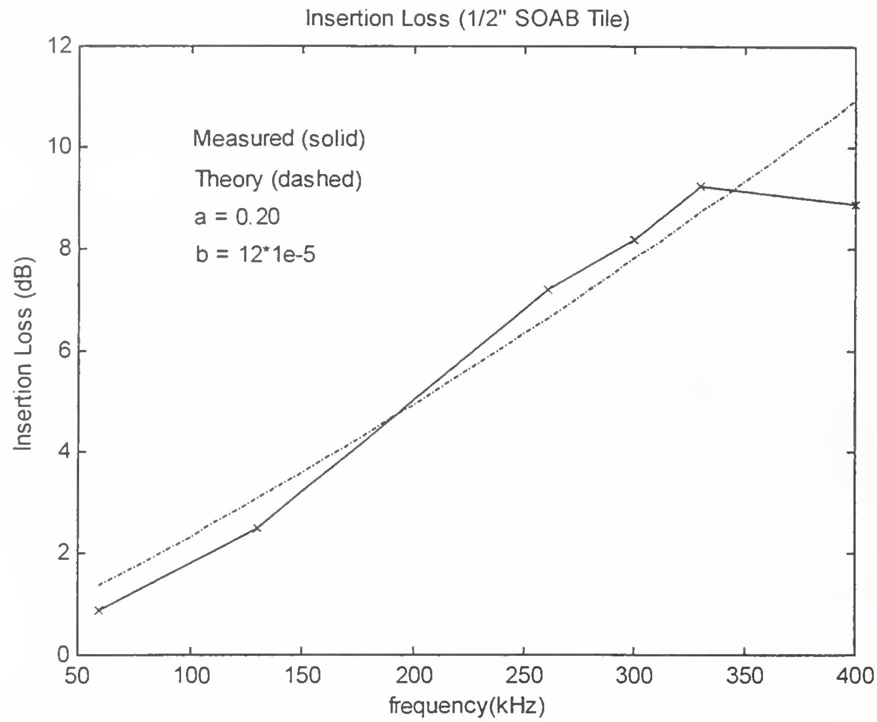


Figure 3.7 Experimental And Theory Insertion Loss

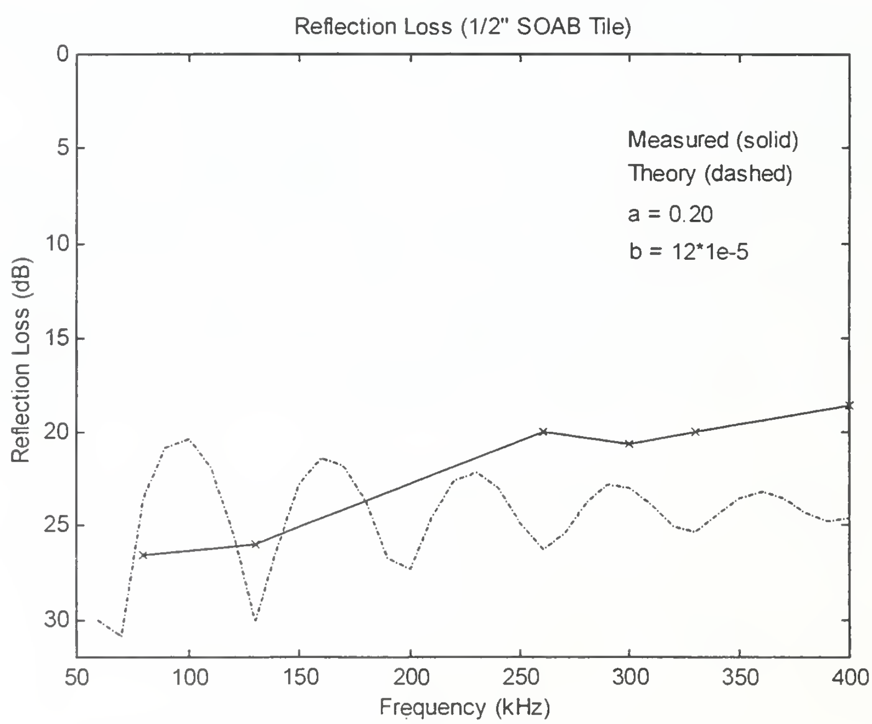


Figure 3.8 Experimental and Theory Reflection Loss

This chapter has explained insertion loss and reflection loss theory and applied it to experimental data. It has also shown that sound absorbing tile (SOAB) is the best material for use as a low pass filter. The next chapter will explain the procedure in using this screen to filter out the dolphins echolocation high frequencies and the effect of its insertion on the animals target detection performance.

IV. BOTTLENOSE DOLPHIN ECHOLOCATION EXPERIMENT

This chapter will discuss the configuration, procedure, and results from the bottlenose dolphin echolocation experiment performed in July 1998 at the Space and Naval Warfare Systems Center (SPAWARSYSCEN), in San Diego. The experiment involved inserting pieces of sound absorbing filters (SOAB) in front of the dolphin and observing the effect on the animal's target detection performance.

A. EXPERIMENTAL CONFIGURATION

The experiment, as shown in Figure 4.1, was performed in a floating pen, surrounded by fish netting and open to San Diego Harbor. The bite plate support, ARL-430 hydrophone, and the SOAB filters were attached on one side of the pen. The targets were hung from the other side of the pen. The bite plate support, as shown in Figure 4.2, was constructed from 2" PVC pipes and contained a sliding neoprene door. When the neoprene door was lowered by the trainer, there was provided an unobstructed aperture through which the dolphin could project its sonar signals. When raised, the neoprene door blocked the animal's sonar signals from the hydrophone and targets. The bite plate was fixed at a depth of 78 cm.

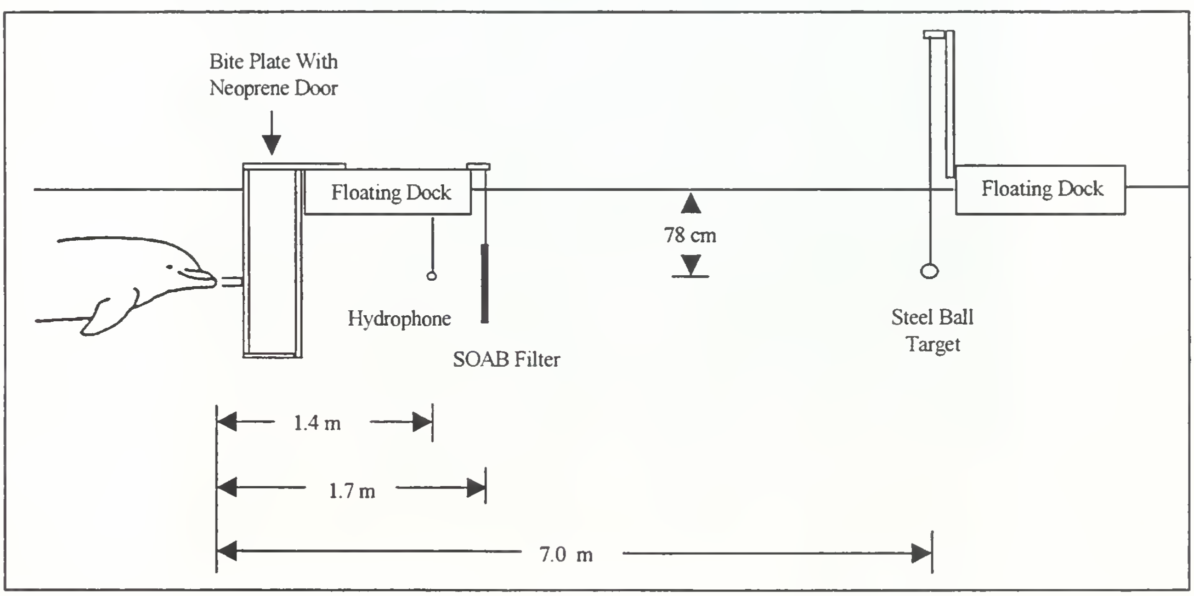


Figure 4.1 Echolocation Experiment Configuration

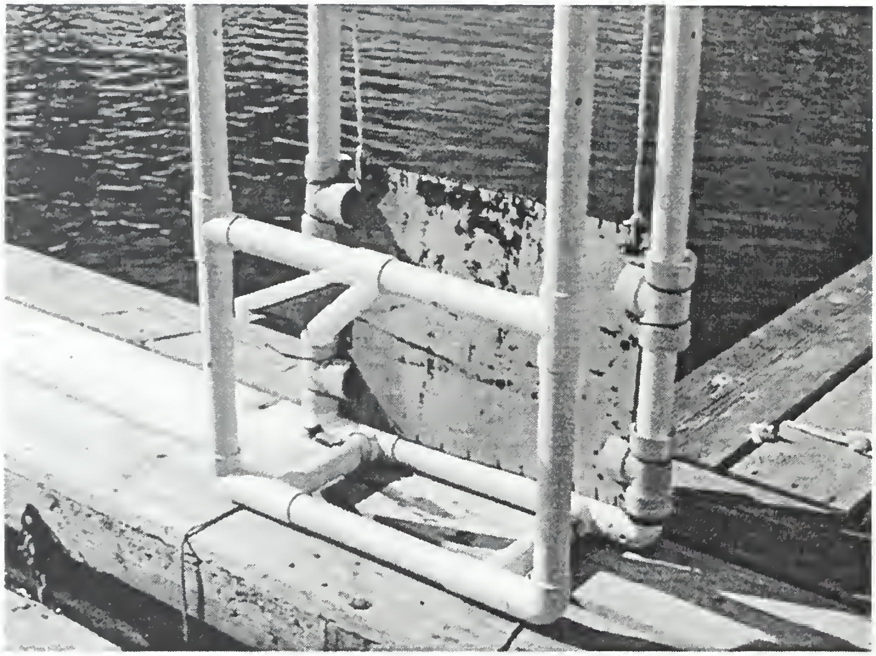


Figure 4.2 Photo of Bite Plate And Neoprene Door Assembly

The ARL-430 hydrophone, shown in Figure 4.3, was placed 1.4 meters from the bite plate and on axis at a depth of 78cm. The hydrophone was connected to a 12-bit National Instruments data acquisition card, which converted analog signals to digital signals. The card was then connected to a personal computer for data collection.

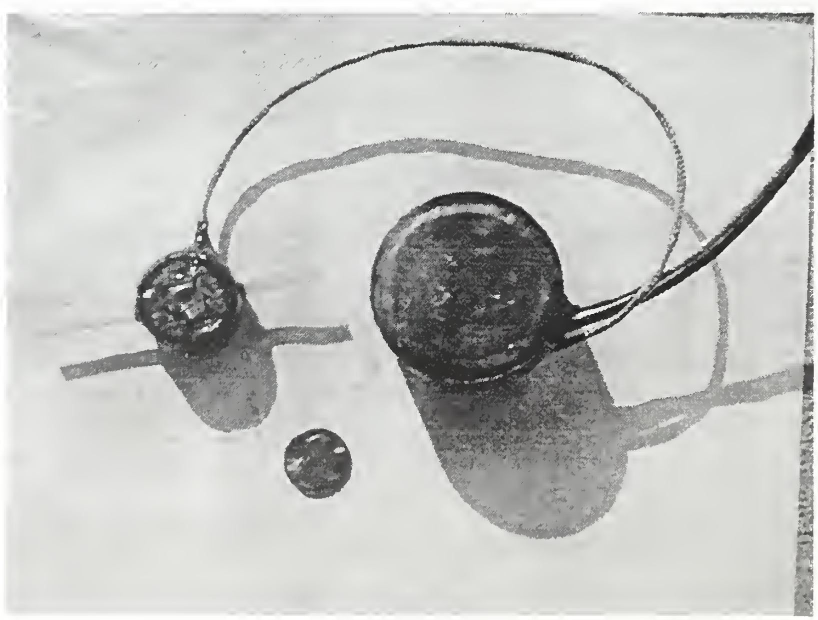


Figure 4.3 Photo of ARL-430 Hydrophone And Preamplifier Next to a Penny

The SOAB filters were attached to square frames made from 1" PVC piping. All of the PVC piping had holes drilled in them which allowed the pieces to be filled with seawater as they were submerged. The filters were hung 1.8 m from the bite plate and the middle of the filter was on axis at a depth of 78 cm. The filters were rigged such that the down position was well below the bite plate support and out of the dolphins sonar beam. In the up position the SOAB filters were centered on axis with the bite plate so that the animal's sonar beam had to penetrate the filter.

The "target," as shown in Figure 4.4, consisted of a 8cm diameter, stainless steel, water-filled sphere. A thin monofilament line was used to lower the target to a depth of 78 cm or raise it out of the water. The "target absent" line contained just a lead weight with no steel sphere. Lead weights were hung at the same depth from both lines to keep tension on the lines. The lead weight on the "target present" line was attached a meter below the steel ball. Both targets were hung at a distance of 7 m from the bite plate. A photo of the experimental configuration is shown in Figures 4.5.

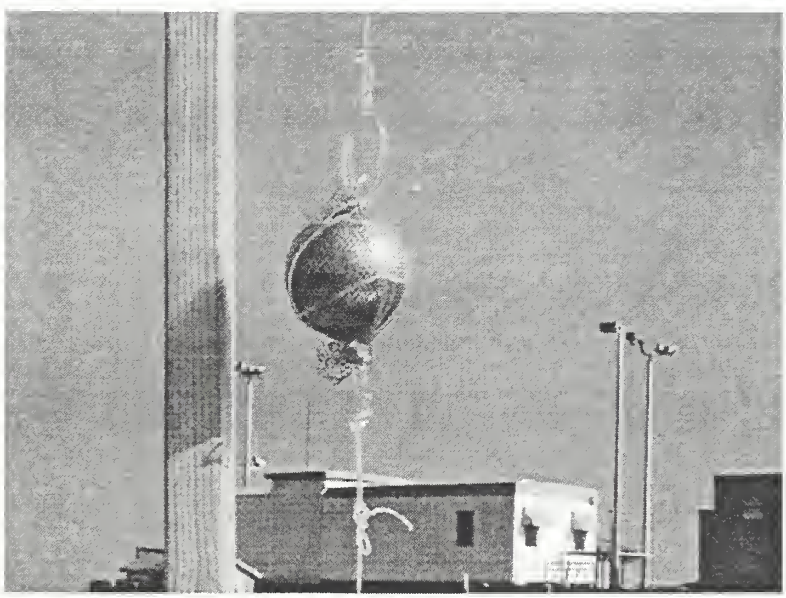


Figure 4.4 Photo of Stainless Steel Water Filled Sphere Target
Next To A 4x4 Wood Post

Figure 4.5 Photo of Experiment Configuration Showing Bite Plate and Target Stand

B. EXPERIMENTAL PROCEDURE

Figure 4.6 shows the trainer first placing suction cups over the dolphin's eyes to prevent it from seeing during the trials. The dolphin was then required to station on the bite plate while the neoprene door remained in the up position. A trial started when the trainer lowered the door, cueing the dolphin to commence its sonar search. After completing the sonar search, the dolphin would respond with a whistle to indicate "target present" response, or remain quiet to indicate "target absent" response. If the dolphin provided the correct response, the trainer would signal the dolphin with a "bridge." A "bridge" is a high pitch whistle that signals the dolphin to leave the bite plate and return to the surface for a reward (usually fish or squid). If the dolphin gave the incorrect response, the trainer would signal a "delta" to the dolphin. A "delta" is a tone that informs the dolphin it made the wrong choice and would not receive any reward. Figure 4.7 shows the trainer signaling the dolphin with a device, that produces the high pitch whistle or tone, known as a "Bundy Box."

Four sets of 20 trials were performed on one bottlenose dolphin named Slooper. A random sequence of trials presenting combinations of target, or no target, filter, or no

filter, was serially offered to the animal. The first set of 20 trials consisted of an empty frame with no SOAB filter. The second set presented a framed ¼" SOAB filter. The third set presented a framed ½" SOAB filter. The last set presented a framed ¾" SOAB filter which was constructed from the ¼" and ½" SOAB tiles mounted on one frame.

Figure 4.6 Photo of Trainer Placing Eye Cups on Dolphin

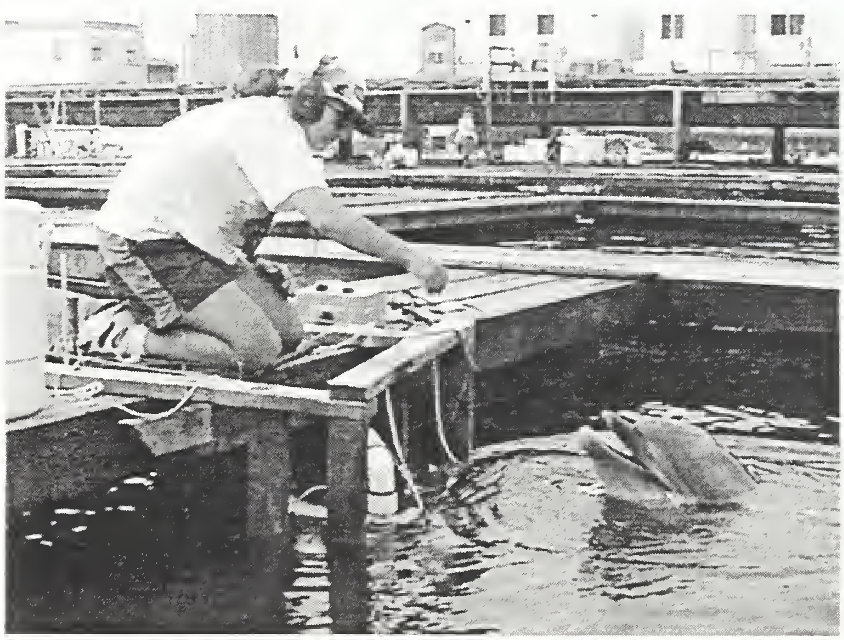


Figure 4.7 Photo of Trainer Signaling Dolphin With Bundy Box

C. EXPERIMENTAL RESULTS

1. Target Recognition

The results from the three sets of trials containing the framed SOAB filters are shown in Tables 4.1 through 4.3. Incorrect responses are shown highlighted. Looking at the results from the three sets of data, one might first conclude that the ¼" SOAB filter produced little effect to the dolphin's echolocation ability, while the ½" and ¾" SOAB filters possibly impaired the dolphin's echolocation ability. A closer look at the data reveals that the SOAB filters, in this experimental configuration, probably had little or no effect on the dolphin's echolocation ability. In the first test, using the ¼" SOAB filter, the dolphin was perfect in identifying the presence of a target from no target. In the second test, using the ½" SOAB filter, the dolphin was incorrect in four responses. Three of these four incorrect responses occurred with no filter present, and possibly was a result of the animal being distracted during the individual trial. In the third test, using the ¾" SOAB filter, the dolphin gave only one incorrect response, and again occurred when no filter was present.

TRIAL NUMBER	TARGET PRESENT	FILTER PRESENT	DOLPHIN RESPONSE	DOLPHIN DECISION
1	YES	NO	WHISTLE	CORRECT
2	YES	NO	WHISTLE	CORRECT
3	YES	NO	WHISTLE	CORRECT
4	NO	YES	QUIET	CORRECT
5	NO	YES	QUIET	CORRECT
6	NO	YES	QUIET	CORRECT
7	NO	NO	QUIET	CORRECT
8	YES	YES	WHISTLE	CORRECT
9	NO	NO	QUIET	CORRECT
10	NO	NO	QUIET	CORRECT
11	NO	YES	QUIET	CORRECT
12	YES	YES	WHISTLE	CORRECT
13	NO	YES	QUIET	CORRECT
14	YES	NO	WHISTLE	CORRECT
15	YES	YES	WHISTLE	CORRECT
16	YES	YES	WHISTLE	CORRECT
17	YES	NO	WHISTLE	CORRECT
18	NO	NO	QUIET	CORRECT
19	NO	NO	QUIET	CORRECT
20	YES	YES	WHISTLE	CORRECT

20 - Correct Responses 0 – Incorrect Responses

Table 4.1 Echolocation Test Using ¼" SOAB Tile

TRIAL NUMBER	TARGET PRESENT	FILTER PRESENT	DOLPHIN RESPONSE	DOLPHIN DECISION
1	YES	NO	WHISTLE	CORRECT
2	YES	NO	QUIET	WRONG
3	YES	NO	WHISTLE	CORRECT
4	YES	YES	QUIET	WRONG
5	NO	YES	QUIET	CORRECT
6	NO	YES	QUIET	CORRECT
7	NO	NO	WHISTLE	WRONG
8	NO	YES	QUIET	CORRECT
9	NO	NO	QUIET	CORRECT
10	YES	YES	WHISTLE	CORRECT
11	NO	YES	QUIET	CORRECT
12	YES	YES	WHISTLE	CORRECT
13	YES	NO	WHISTLE	CORRECT
14	NO	NO	WHISTLE	WRONG
15	YES	YES	WHISTLE	CORRECT
16	NO	NO	QUIET	CORRECT
17	YES	NO	WHISTLE	CORRECT
18	YES	YES	WHISTLE	CORRECT
19	NO	NO	QUIET	CORRECT
20	NO	YES	QUIET	CORRECT

16 - Correct Responses

4 – Incorrect Responses: 2 false positives, and
2 false negatives

Table 4.2 Echolocation Test Using ½” Filter

TRIAL NUMBER	TARGET PRESENT	FILTER PRESENT	DOLPHIN RESPONSE	DOLPHIN DECISION
1	YES	NO	WHISTLE	CORRECT
2	NO	NO	QUIET	CORRECT
3	YES	YES	WHISTLE	CORRECT
4	NO	NO	QUIET	CORRECT
5	YES	NO	WHISTLE	CORRECT
6	NO	YES	QUIET	CORRECT
7	YES	NO	WHISTLE	CORRECT
8	NO	NO	QUIET	CORRECT
9	YES	YES	WHISTLE	CORRECT
10	YES	NO	WHISTLE	CORRECT
11	NO	YES	QUIET	CORRECT
12	NO	YES	QUIET	CORRECT
13	YES	NO	QUIET	WRONG
14	YES	YES	WHISTLE	CORRECT
15	NO	NO	QUIET	CORRECT
16	NO	NO	QUIET	CORRECT
17	NO	YES	QUIET	CORRECT
18	YES	YES	WHISTLE	CORRECT
19	NO	YES	QUIET	CORRECT
20	YES	YES	WHISTLE	CORRECT

19 - Correct Responses

1 – Incorrect Response: false negative

Table 4.3 Echolocation Test Using ¾” Filter

2. Time Duration Of Click Trains

The duration of the dolphin click train (average time), in seconds, is shown in Table 4.4. The rows in the table represent each of the recorded data sets, where a different size filter was attached to the PVC frame. The columns represent the different presentations of target and filter present or not present during the individual data set of 20 trials. Comparing the first two columns, the click train is shorter when the target and filter were both presented to the dolphin. This indicates that the dolphin was able to identify the presence of the target just the same with or without the filter present. When there was no target present, the click train length was considerably longer indicating that the animal was really searching for the target before it decided it was absent. The last two columns show that the click train length increased even more when the filter and no target was presented to the dolphin. This trend appears to suggest that the filter caused some difficulty in the dolphin's ability to ensure that the target was in fact absent.

DATA SET	TARGET NO FILTER	TARGET FILTER	NO TARGET NO FILTER	NO TARGET FILTER
EMPTY FRAME	1.37 sec	0.792 sec	1.29 sec	1.72 sec
¼" FILTER	1.11 sec	0.742 sec	1.76 sec	2.06 sec
½" FILTER	1.07 sec	1.02 sec	1.62 sec	2.18 sec
¾" FILTER	1.15 sec	1.12 sec	2.14 sec	2.19 sec

Table 4.4 Dolphin Click Train Average Time During Echolocation Trials

3. Click Energy Flux Spectral Density

Figures 4.8 through 4.11 show eight clicks overlapping from the maximum amplitude portion of a click train and its corresponding energy flux spectral density. The standard deviation of the eight signal's energy flux spectral density is also shown on the plot as a dot-dashed line. The signals analyzed were chosen from a trial, representing each of the four data sets, when a target was present and the dolphin correctly identified the target. The figures show an increase in the time series click amplitude and respective energy flux spectral density as the thickness of filter increases. The energy present at the peak frequency around 130 kHz remains constant through the four trials, but the energy between 250 kHz and 500 kHz increases as the dolphin attempts to penetrate the thicker

SOAB filter with its sonar. It appears that the dolphin is utilizing a portion of the higher frequency components to identify the presence of a target. The dolphin is also having to increase its signal amplitude to penetrate the thicker filter.

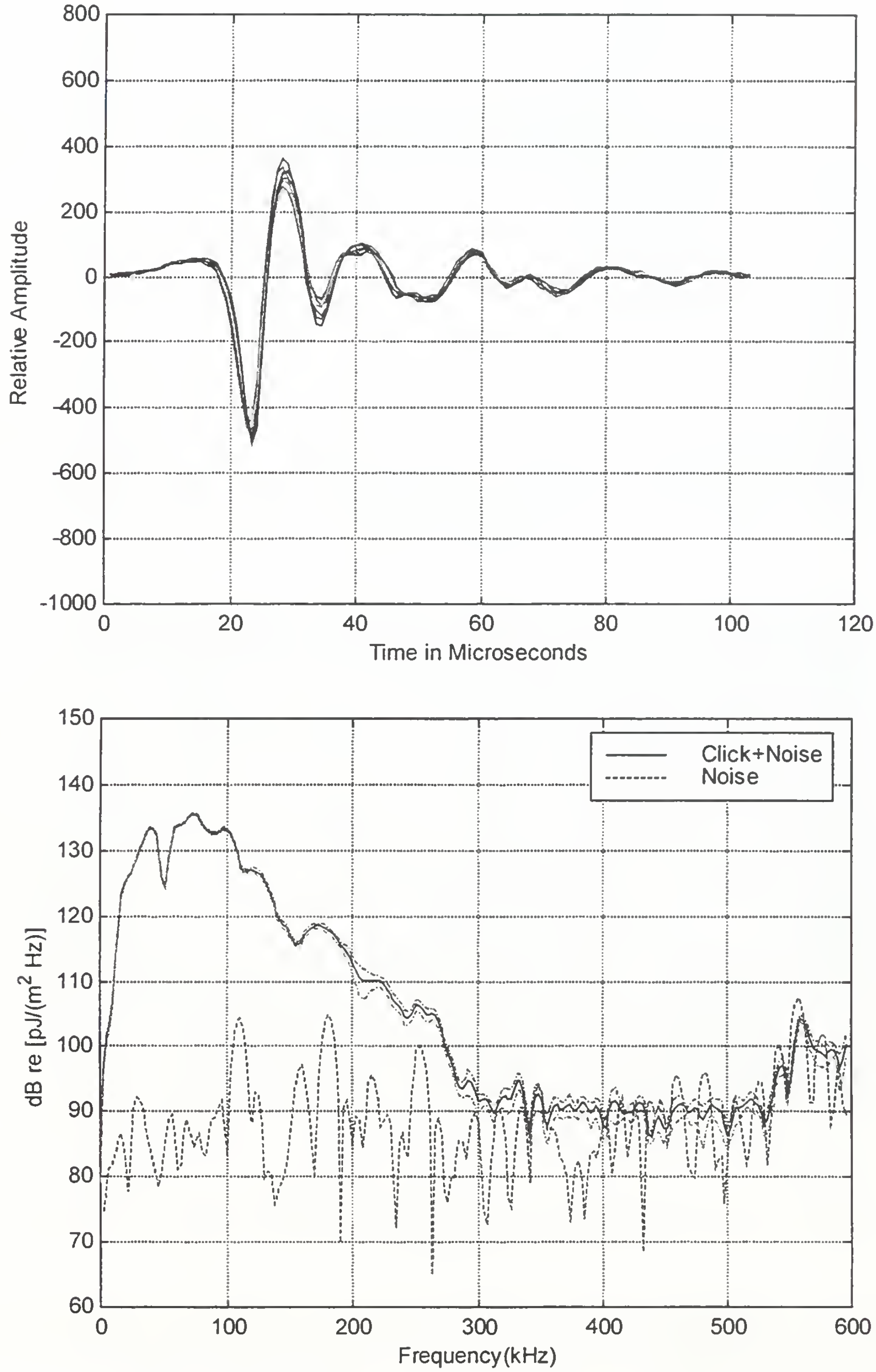


Figure 4.8 Eight Dolphin Clicks And Corresponding Average Energy Flux Spectral Density With No Filter Present (± 1σ shown as dot-dash line)

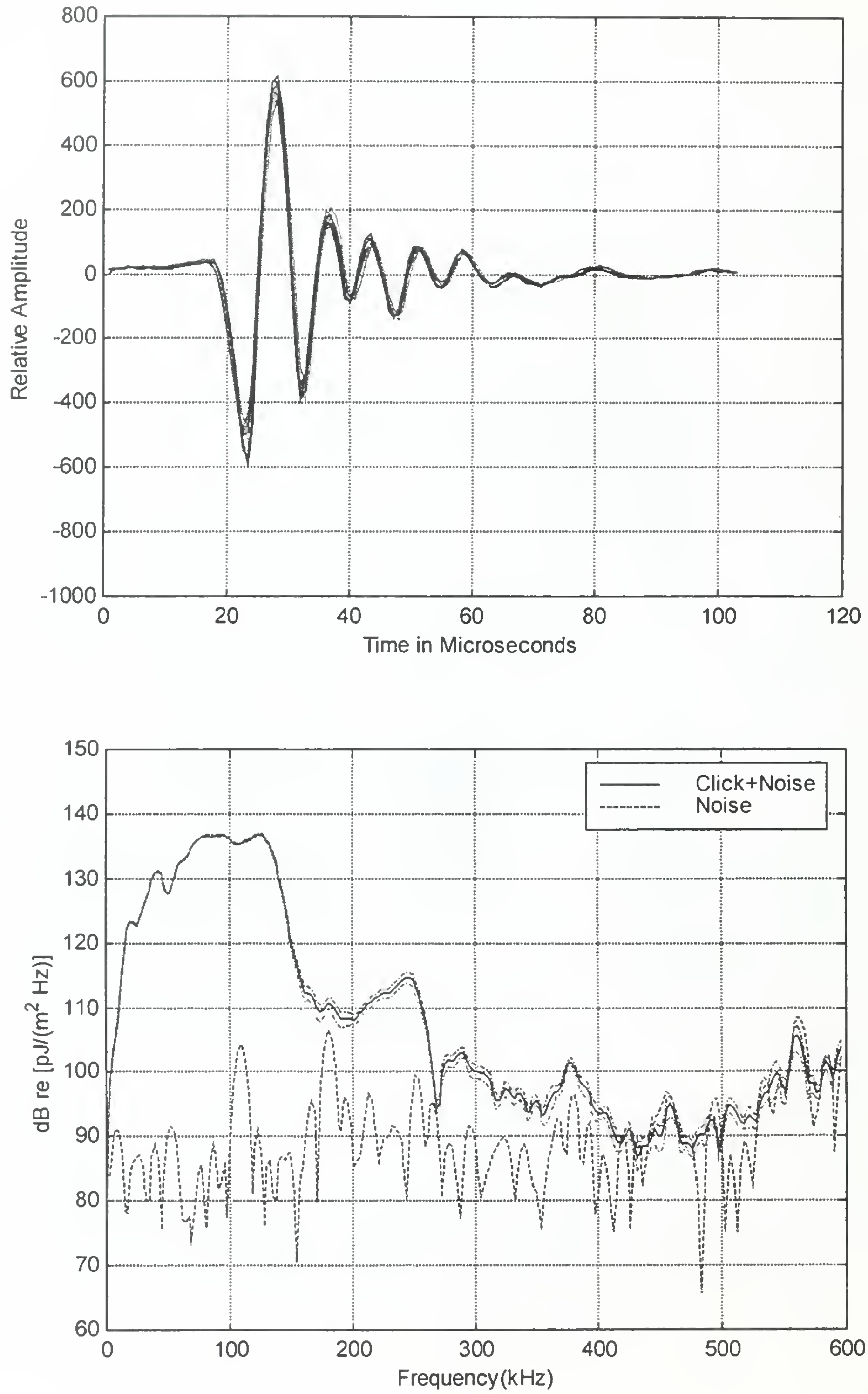


Figure 4.9 Eight Dolphin Clicks And Corresponding Average Energy Flux Spectral Density With ¼" Filter Present (± 1 σ shown as dot-dash line)

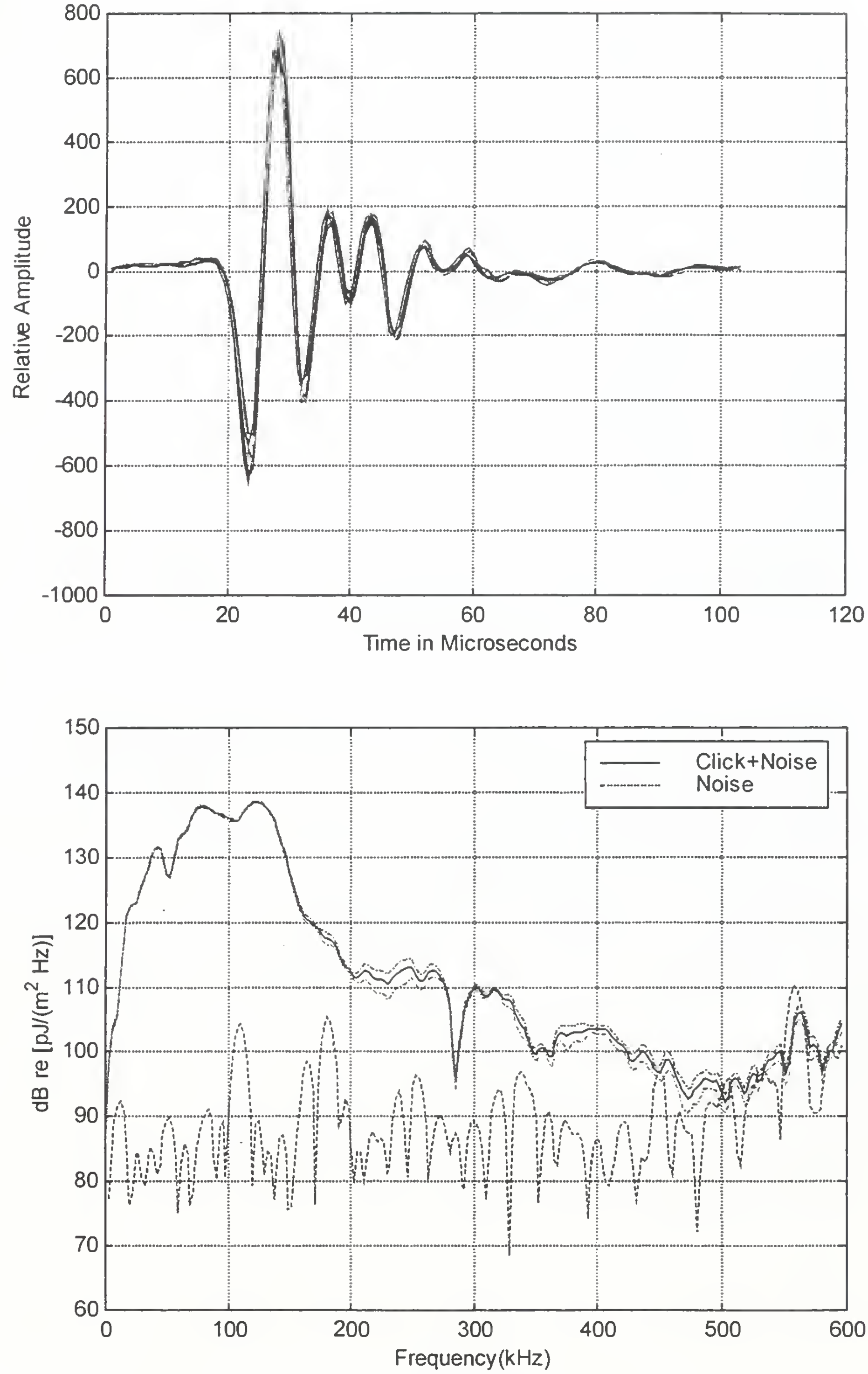


Figure 4.10 Eight Dolphin Clicks And Corresponding Average Energy Flux Spectral Density With ½" Filter Present (± 1 σ shown as dot-dash line)

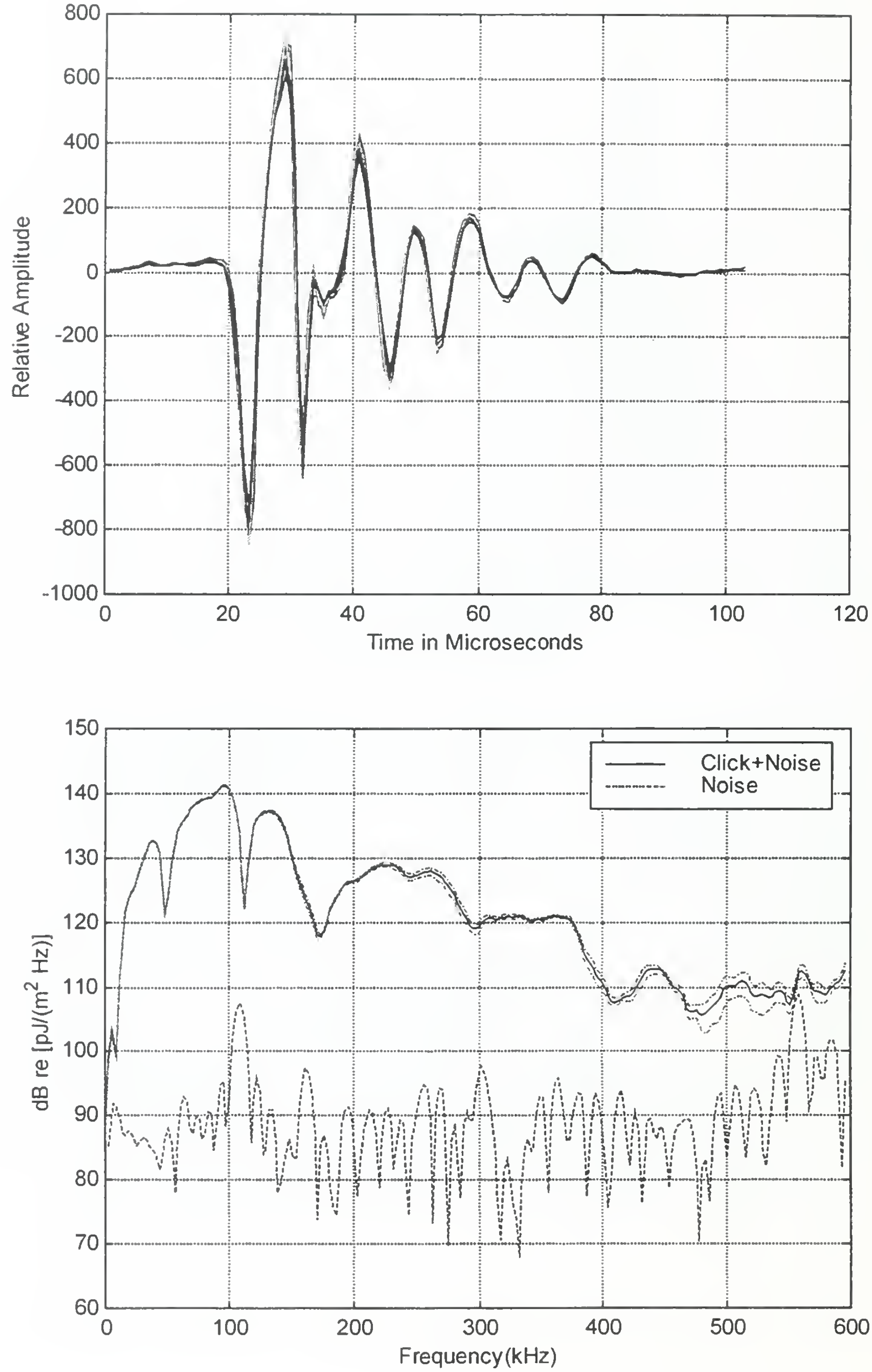


Figure 4.11 Eight Dolphin Clicks And Corresponding Average Energy Flux Spectral Density With ¾" Filter Present (± 1σ shown as dot-dash line)

4. Diffraction As A Source Of Experimental Uncertainty

One possible explanation of why the dolphin's echolocation performance appeared to be unaffected during the insertion of acoustic high-frequency filters could be that a portion of the dolphin's sonar beam passed around the filter, as depicted in Figure 4.12.

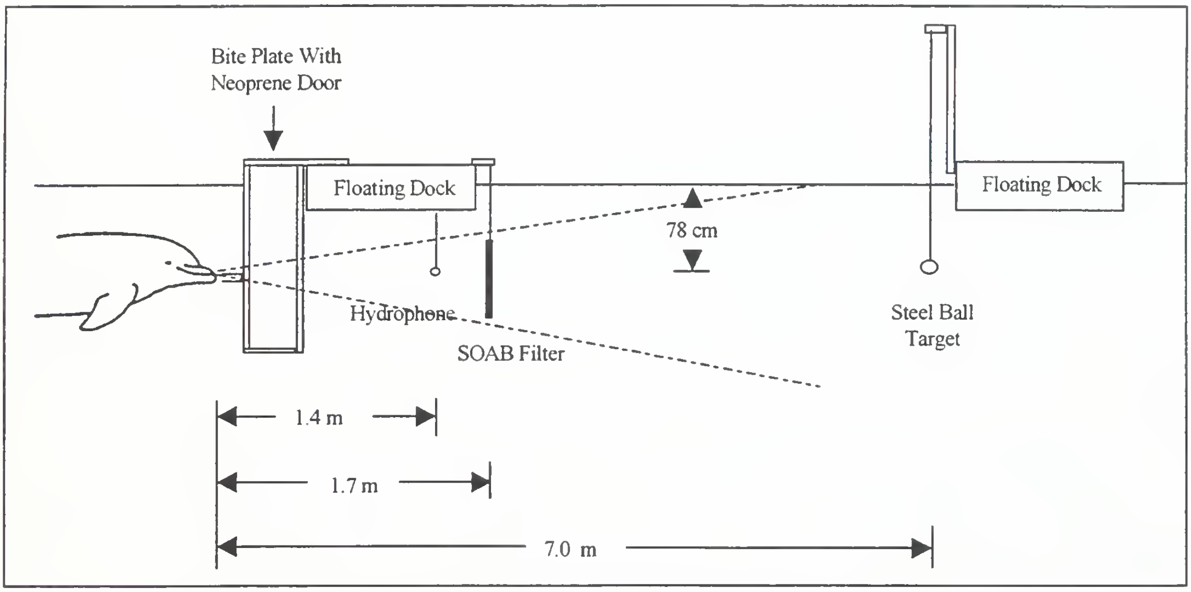


Figure 4.12 Echolocation Experiment Showing Dolphin's Projected Sonar Beam

Au calculated the average 3-dB and 10-dB vertical beam widths of three bottlenose dolphin transmitted sonar beams, centered at 130 kHz, to be 10.2° and 22.5° respectively [Ref. 2]. The width of a sonar beam at the distance of the filter (1.7m) can be calculated from the relation $s=r\theta$, where s is the surface area, r is the radius, and θ is the beam width in radians. Using this relation, the vertical extent of the dolphin's sonar beam at the filter would have been 30 cm for the 3-dB beam width, and 68 cm for the 10-db beam width. The width of the ¼" SOAB filter was 53cm, and the width of the ½" SOAB filter was 28cm. These results indicate that a portion of the dolphin's sonar beam was not entirely blocked by the filter. No measurements were recorded in this experiment to indicate whether or not diffracted paths were important. Future experiments must ensure the filter is placed closer to the dolphin to ensure the filter blocks the entire sonar beam.

This chapter has discussed the configuration, procedure and some significant results from an echolocation target detection task with the presence of sound absorbing filters. Although this experiment has not provided conclusive evidence on the dolphin's use of high frequency components during echolocation, it has shown clear evidence that some compensation was made by the dolphin for the sound absorption caused by the insertion of the filter.

V. CONCLUSIONS AND RECOMMENDATIONS

This final chapter briefly synopsizes the noteworthy observations made during the conduct of the research described in this thesis and the conclusions that can be drawn from these observations. It also provides further recommendations for continuing research efforts.

The first objective of this thesis was to verify the existence of high frequency components in bottlenose dolphin echolocation signals. The second chapter clearly showed the existence of high frequency energy components in a dolphin click. Using a wide-band hydrophone allowed the high frequency components to become visible. The comparison of a sequence of clicks from the steady maximum amplitude portion of the click train also showed that if the high frequency components are present in one click, then they are present in adjacent clicks, to an amazing degree of uniformity and repeatability.

The second objective was to obtain and test an absorbing material capable of filtering out the higher frequency components in the dolphin's sonar signal. The third chapter concluded that sound absorbing material (SOAB) best resembles a low pass filter capable of absorbing a major portion of the high frequency sonar signal components. The material was also found to have very little reflectivity. Acoustically, this material would be ideal since, in theory, the dolphin would unlikely be able to detect the presence of the filter within its sonar beam.

The final objective was to observe whether the dolphin's echolocation ability was impaired by the presence of sound absorbing material placed in its beam, and so to determine whether the high frequency components are being used by the animal for sonar data acquisition. The fourth chapter discussed the first time a dolphin echolocation target detection experiment was conducted using various dimensions of SOAB material within the dolphin's sonar beam. Even though the results of this one experiment where inconclusive in answering the third thesis objective, it did accomplish filter testing with a live animal where follow-on efforts can begin. It was difficult to conclude if the dolphin was impaired at all by the presence of the various SOAB filters. The dolphin was confident in reporting the presence of a target using all three filters. The animal was also

definitely compensating for the filters, by increasing its sound energy output, especially for frequencies above 100 kHz. The dolphin's few errors may have been a result of animal distraction or from being exposed to a new experimental configuration that the animal was not accustomed to. It is possible that a small portion of the animal's sonar beam was not blocked by the filters, due to their position in the experiment. The only way to determine the true effect of the filters on the dolphin's echolocation ability is to conduct many more trials with different experimental configurations.

Many questions remain unanswered in reference to the dolphin sonar system. Analysis of the echolocation data collected in 1997 and recent 1998 trials could provide even further direction toward future research.

This thesis has provided a stepping stone toward future work in discovering an alternative mine-hunting system, which is less expensive and has a higher search rate than the marine mammal.

APPENDIX A. ENERGY FLUX SPECTRAL DENSITY ANALYSIS

This appendix contains the MATLAB programs used to conduct the energy flux spectral density analysis of a dolphin click.

```
%Filename: dolphinspec.m
%Author:  R.W. Toland
%Date Last Modified: 14 April 1998
%Purpose: This program calculates the energy flux spectral density
%         level in a dolphin click and plots click+noise and noise
%         prior to click using MATLAB Normalization (Parseval's
%         Relation) and shows that the time plot energy equals the
%         frequency plot energy.

clear all
%open noise data file
fidn = fopen('d:\toland\data\noiseprior');
%read data file that is in binary short integer format;
sign = fread(fidn,inf,'short');
%normalize the signal
sign = sign(1:128);
sign1 = sign - mean(sign);
Nndat = length(sign1);

%open click data file
fidc = fopen('d:\toland\data\clickfc');
%read data file that is in binary short integer format;
sigc = fread(fidc,inf,'short');
%normalize the signal
sigc = sigc(1:128);
sigc1 = sigc(1:128) - mean(sigc);
Ncdat = length(sigc1);

%Sampling Frequency
Fs = 1250000;
%period of signal
time = (1:Ncdat)/Fs;
%convert time to microseconds
time1 = time.*1000000;
%plot click
figure(1)
plot(time1,sigc1)
title('Bottlenosed Dolphin Echolocation Click')
xlabel('Time in Microseconds')
ylabel('Relative Amplitude')

%fft points
Nfft = 512;
%calculate fft of noise
DFT = fft(sigc1,Nfft);
%convert data points to frequency
w = (0:((Nfft/2)-1))/(Nfft/2)*(Fs/2);
%convert frequency to kHz
```

```
w1 = w./1000;

%PSD of noise prior click
[Pxxn,fn] = psd(sign1,Nfft,Fs,boxcar(Nfft),0);
%Multiply by 2*Nfft/Fs to get true PSD
Pxxn1 = Pxxn.*(2*Nfft/Fs);
%Convert to dB scale
Pxxndb = 10*log10(abs(Pxxn1));

%PSD of click + Noise
[Pxxc,fc] = psd(sigc1,Nfft,Fs,boxcar(Nfft),0);
%Multiply by 2*N/Fs to get true PSD
Pxxc1 = Pxxc.*(2*Nfft/Fs);
%Convert to dB scale
Pxxcdb = 10*log10(Pxxc1);
N = length(Pxxcdb);

%Change units of Energy Spectral Density Plot(dB ref 1picoJoule/m^2-Hz
at 1m)
f1 = hydrocal(fn);
%correction for hydrophone (-dB sensitivity from chart)
Clickdb = Pxxcdb-f1;
Noisedb = Pxxndb-f1;
%correction for gain (-20log(gain)), and range (+20log(d)), correction
for energy (-10log(pc))
Pxxcdb_new = Clickdb - 14 + 20.*log10(1.38)-10.*log10(1.5e6);
Pxxndb_new = Noisedb - 14 + 20.*log10(1.38)-10.*log10(1.5e6);

%Plot both (Click + Noise) and (Noise prior click) on same plot
figure(2)
plot(fn(1:245)./1000,Pxxcdb_new(1:245),'-
',fc(1:245)./1000,Pxxndb_new(1:245),'-.')
title('Energy Flux Spectral Density Level vs Frequency')
xlabel('Frequency(kHz)')
ylabel('Energy Flux Spectral Density Level dB re [pJ/(m^2 Hz)]')
legend('Click+Noise','Noise')

%Energy in frequency domain = Energy in time domain
energy_from_time_click = sum(sigc1.^2)
energy_from_freq_click = 2*sum(Pxxc)

energy_from_time_noise = sum(sign1.^2)
energy_from_freq_noise = 2*sum(Pxxn)
```

```
%Filename: hydrocal.m
%Author:  R.W. Toland
%Date Last Modified: 14 April 1998
%Purpose:  This function plots the ARL 430 hydrophone sensitivity curve
%          out to the first 600 Hz to apply to dolphinspec.m for
%          converting PSD plot to pressure units.  The curve is
%          approximated by polyfit function.

function f1 = hydrocal(fn)
N = 600;
inta = round(225/600*N);
intb = inta + round(75/600*N);
intc = intb + round(80/600*N);
intd = intc + round(70/600*N);
inte = intd + round(70/600*N);
intf = inte + round(30/600*N);
intg = intf + round(40/600*N);
y1 = -194.*ones([inta,1]);
for j = 1:(intb-inta)
   y2(j) = y1(length(y1))-j*(0.04);
end
clear j;
for j = 1:(intc-intb)
   y3(j) = y2(length(y2))-j*(0.013);
end
clear j;
y4 = y3(length(y3)).*ones([(intd-intc),1]);
for j = 1:(inte-intd)
   y5(j) = y4(length(y4))-j*(0.0536);
end
clear j;
for j = 1:(intf-inte)
   y6(j) = y5(length(y5))-j*(0.143);
end
clear j;
for j = 1:(intg-intf)
   y7(j) = y6(length(y6))-j*(.03);
end
sum_y = [y1',y2,y3,y4',y5,y6,y7];
i = linspace(1,600,length(sum_y));
p = polyfit(i,sum_y,9);
f = polyval(p,(1:length(sum_y)));

f1 = polyval(p,(fn./1000));
```

APPENDIX B. CORRELATION COEFFICIENT ANALYSIS

This appendix contains the MATLAB program used to conduct correlation coefficients and comparison analysis of five consecutive dolphin clicks from a click train.

```
%Filename:  correlate.m
%Author:  R.W. Toland
%Date Last Modified: 29 January 1998
%Purpose: This program loads five dolphin clicks containing 128 pts
%         each, and correlates each click to one of the other five,
%         producing a matrix of correlation coefficients.  It then
%         plots the comparison of overlapping signals.

clear all
%open data file
fida = fopen('d:\toland\data\click1');
%read data file that is in binary short integer format;
clicka = fread(fida,inf,'short');
%normalize the signal
sig1 = clicka - mean(clicka);
N = length(sig1);

%open data file
fidb = fopen('d:\toland\data\click2');
%read data file that is in binary short integer format;
clickb = fread(fidb,inf,'short');
%normalize the signal
sig2 = clickb - mean(clickb);
Nn = length(sig2);

%open data file
fidc = fopen('d:\toland\data\click3');
%read data file that is in binary short integer format;
clickc = fread(fidc,inf,'short');
%normalize the signal
sig3 = clickc - mean(clickc);
Nc = length(sig3);

%open data file
fidd = fopen('d:\toland\data\click4');
%read data file that is in binary short integer format;
clickd = fread(fidd,inf,'short');
%normalize the signal
sig4 = clickd - mean(clickd);
Nc = length(sig4);

%open data file
fide = fopen('d:\toland\data\click5');
%read data file that is in binary short integer format;
clicke = fread(fide,inf,'short');
```

```
%normalize the signal
sig5 = clicke - mean(clicke);
Nc = length(sig5);

%Sampling Frequency
Fs = 1250000;
%period of signal
time = (1:N)/Fs;
%convert time to microseconds
time1 = time.*1000000;

max_corr = [];

for i = 1:5
  file1 = ['sig',num2str(i)];
  for j = 1:5
    file2 = ['sig',num2str(j)];
    corr = xcorr(eval(file1),eval(file2),'coeff');
    [mx,indx] = max(abs(corr));
    max_corr(i,j) = mx;
    index(i,j) = indx;
  end
end

Correlation_Coefficient_Matrix = max_corr
Index_Matrix = index

for k = 1:129
   sig1_new(k+1,1) = sig1(k,1);
   sig3_new(k+1,1) = sig3(k,1);
   sig4_new(k+1,1) = sig4(k,1);
   sig5_new(k+1,1) = sig5(k,1);
end

%plot signal
figure(1)
plot(time1,sig1_new(1:129),time1,sig2,time1,sig3_new(1:129),time1,...
     sig4_new(1:129),time1,sig5_new(1:129))
   title('Comparison of Five Consecutive Dolphin Clicks')
xlabel('Time in Microseconds')
ylabel('Relative Amplitude')
```

APPENDIX C. SOUND ABSORPTIVE SCREEN (SOAB) ANALYSIS

This appendix contains the MATLAB programs used to conduct the insertion loss, reflection loss and theory analysis of SOAB.

```
%Filename: insertionloss.m
%Author:  R.W. Toland
%Date Last Modified:  22 May 1998
%Purpose:  This program calculates the insertion loss for three
%          different sizes of SOAB material.

clear all
%frequencies of measurements
freq = [130 240 250 270 290 340];
%no tile hydrophone receive voltage
Vo = [5.8 8.0 10.4 11.6 9.2 4.4];
Vo1 = [10.8 11.2 12.4 12.8 10.4 5.6];
Vo2 = [1.5 7.2 9.4 14.0 14.4 6.0];
%with tile hydrophone receive voltage
V1 = [.7 1.5 1.75 2.1 2.1 1.45];
V2 = [2.0 3.6 4.4 5.0 4.2 2.2];
V3 = [.08 .5 .7 1.2 1.4 .7];
V4 = [.8 3.1 3.8 5.3 5.8 2.3];
%calculate insertion loss
TL1 = 20.*log10(Vo./V1);
TL2 = 20.*log10(Vo1./V2);
TL3 = 20.*log10(Vo2./V3);
TL4 = 20.*log10(Vo2./V4);
%plot figure
plot(freq,TL1,freq,TL1,'o',freq,TL2,':',freq,TL2,'o',freq,TL3,'.-',...
freq,TL3,'o',freq,TL4,freq,TL4,'o')
title('Tile 1 - thin, vacuum, no bubbles')
xlabel('frequency(kHz)')
ylabel('Transmission Loss(dB)')
```

```
%Filename: insertionangle.m
%Author:  R.W. Toland
%Date Last Modified:  22 May 1998
%Purpose:  This program calculates the insertion loss as a function
%          of angle off axis.

clear all
%frequency of measurements
freq = [60 120 130 160 260 280 290 300 310 330 370 400];
%hydrophone recieve voltage
Vo = [2.45 4.1 3.7 1.7 2.85 3.6 3.7 3.3 2.9 2.55 1.9 1.5];
V1 = [2.25 3.3 2.95 1.16 1.36 1.65 1.6 1.48 1.32 1.02 .66 .58];
V2 = [2.25 3.2 2.9 1.25 1.36 1.65 1.6 1.4 1.28 1.02 .64 .58];
V3 = [2.2 3.2 2.9 1.25 1.3 1.55 1.5 1.38 1.22 1.22 .64 .56];
V4 = [2.2 3.15 2.85 1.2 1.25 1.5 1.45 1.35 1.2 .92 .6 .52];
```

```
%calculate insertion loss
TL1 = 20.*log10(Vo./V1);
TL2 = 20.*log10(Vo./V2);
TL3 = 20.*log10(Vo./V3);
TL4 = 20.*log10(Vo./V4);
%plot figure
plot(freq,TL1,freq,TL1,'x',freq,TL2,':',freq,TL3,'.-
',freq,TL4,freq,TL4)
title('SOAB Insertion Loss As A Function Of Angle Off Axis')
xlabel('Frequency(kHz)')
ylabel('Insertion Loss(dB)')
legend('SOAB','','SOAB-5deg','SOAB-10deg','SOAB-20deg')
```

```
%Filename: iltheory.m
%Author:  R.W. Toland
%Date Last Modified:  22 May 1998
%Purpose:  This program calculates the insertion loss for 1/2" SOAB
%          filter and compares it to theory.

clear all
freq = [60 130 260 300 330 400].*1e3;
%hydrophone receive voltage
Vo = [4.2 6.0 3.2 4.1 3.7 2.0];
V2 = [3.8 4.5 1.4 1.6 1.28 0.72];
TL2 = 20.*log10(Vo./V2);
%plot measured values
plot(freq./1000,TL2,'-',freq./1000,TL2,'x')
title('Insertion Loss Of 1/2" SOAB Tile')
xlabel('frequency(kHz)')
ylabel('Insertion Loss(dB)')
%grid
hold on
p = polyfit(freq,TL2,3);
freq_theory = [60 130 260 300 330 400].*1e3;
TL_theory = polyval(p,freq_theory);

%Insertion Loss Theory
w = 2*pi*freq_theory;

p1 = 1000;     %density fresh water
c1 = 1480;     %speed of fresh water

p2 = 1662;     %density SOAB
c2 = 933.33;   %longitudinal sound speed SOAB
d = .5/39.4;   %thickness in inches converted to meters
k = w./c2;

%longitudinal attenuation
alpha_l = TL_theory.*100./8.7; %conversion of dB/cm to nepers/m

%longitudinal loss parameter
r = alpha_l*c2./w;
```

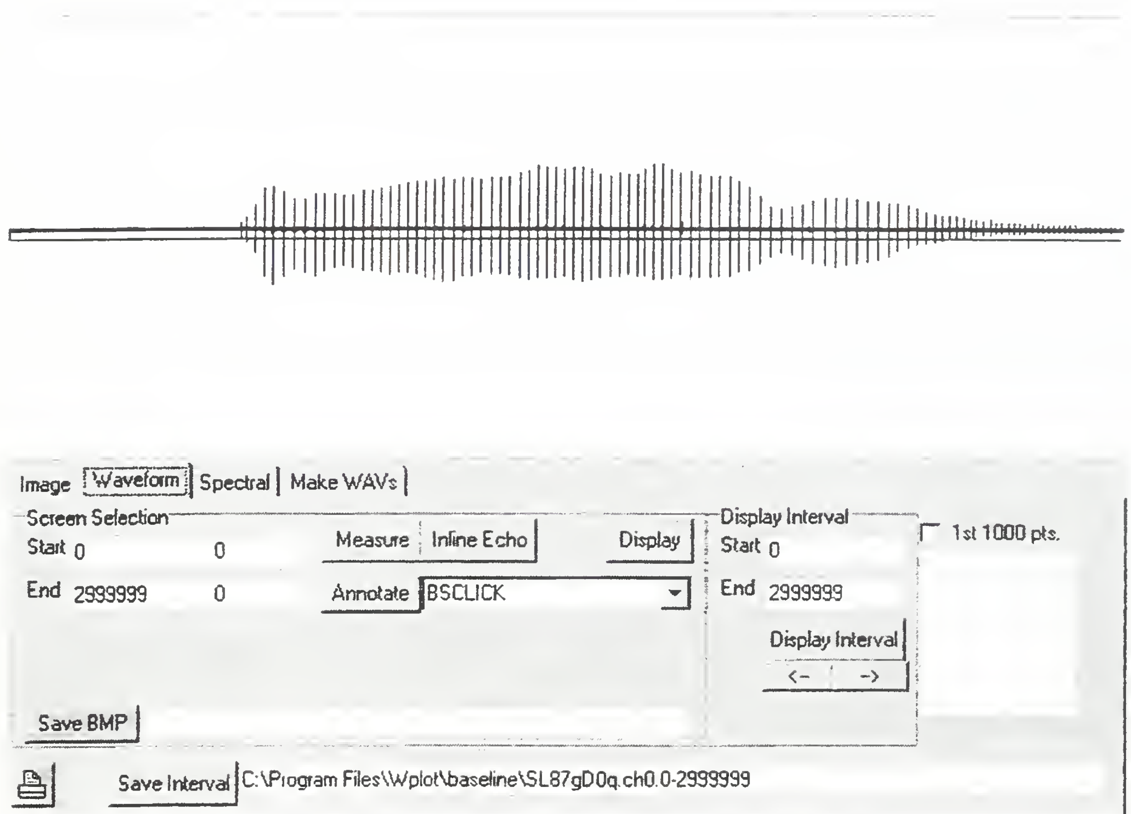
```
Z1 = (p1*c1);
Z2 = (p2*c2);

m = Z2./Z1;
num = ((m+1-j.*r).^2.*exp(j*2.*k*d))-((m-1+j.*r).^2.*exp(-
2.*alpha_l*d));
denom = 4*m*(1-j.*r).*exp((j.*k*d)-(alpha_l*d));
IL = 20*log10(abs(num./denom));
%plot theory
plot(freq_theory./1000,IL,'-.')
gtext('Measured (-)')
gtext('Theory (-.)')
```

```
%Filename: rltheory.m
%Author:  R.W. Toland
%Date Last Modified:  22 May 1998
%Purpose:  This program calculates the reflection loss for 1/2" SOAB
%          filter and compares it to theory.

clear all
freq = [80 130 260 300 330 400];

%SOAB III (1/2")
Vi = [.72 1.6 4.2 8.2 9.0 1.7];
Vr = [.034 .08 .42 .76 .9 .2];
RL = 20.*log10(Vi./Vr);
figure(1)
%plot measured
plot(freq,RL,freq,RL,'x')
title('Reflection Loss (1/2" SOAB Tile)')
xlabel('Frequency (kHz)')
ylabel('Reflection Loss (dB)')
axis([50 400 0 32])
set(gca,'ydir','reverse')
hold on

freq_theory = [60:10:400].*1e3;

%Reflection Loss Theory
w = 2*pi*freq_theory;
p1 = 1000;     %density fresh water
c1 = 1480;     %speed of fresh water
p2 = 993.33; %density SOAB
c2 = 1662;   %longitudinal sound speed SOAB
d = .5/39.4; %thickness in inches converted to meters
k = w./c2;

%longitudinal attenuation (freq in kHz)
a = 0.20;      %Np/m kHZ
b = 12e-5;   %Np/m kHz
alpha_l = (a.*freq_theory./1000)+(b.*(freq_theory./1000).^2);
%longitudinal loss parameter
r = alpha_l*c2./w;
```

```
Z1 = (p1*c1);
Z2 = (p2*c2);
m = Z2./Z1;
num1 = ((m+1-j.*r)./(m-1+j.*r)).*exp((j.*k*d)+(alpha_l*d));
num2 = ((m-1+j.*r)./(m+1-j.*r)).*exp((-j.*k*d)-(alpha_l*d));
denom = exp((j.*k*d)+(alpha_l*d))-exp((-j.*k*d)-(alpha_l*d));
ER = 20*log10(abs((num1-num2)./denom));
%plot theory
plot(freq_theory./1000,ER,'-.')
set(gca,'ydir','reverse')
gtext('Measured (solid)')
gtext('Theory (dashed)')
gtext('a = 0.20')
gtext('b = 12*1e-5')
```

APPENDIX D. WPLOT PROGRAM SAMPLE

This appendix contains an example of the Wplot software used to visually display raw data echolocation recordings. This software allowed large data sets of interest to be cut into manageable files which could then be analyzed in MATLAB. [Ref. 20]



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